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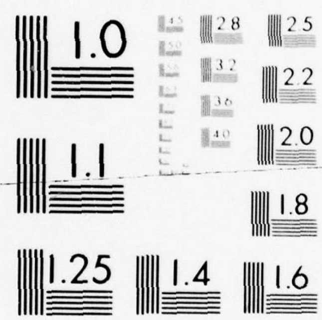

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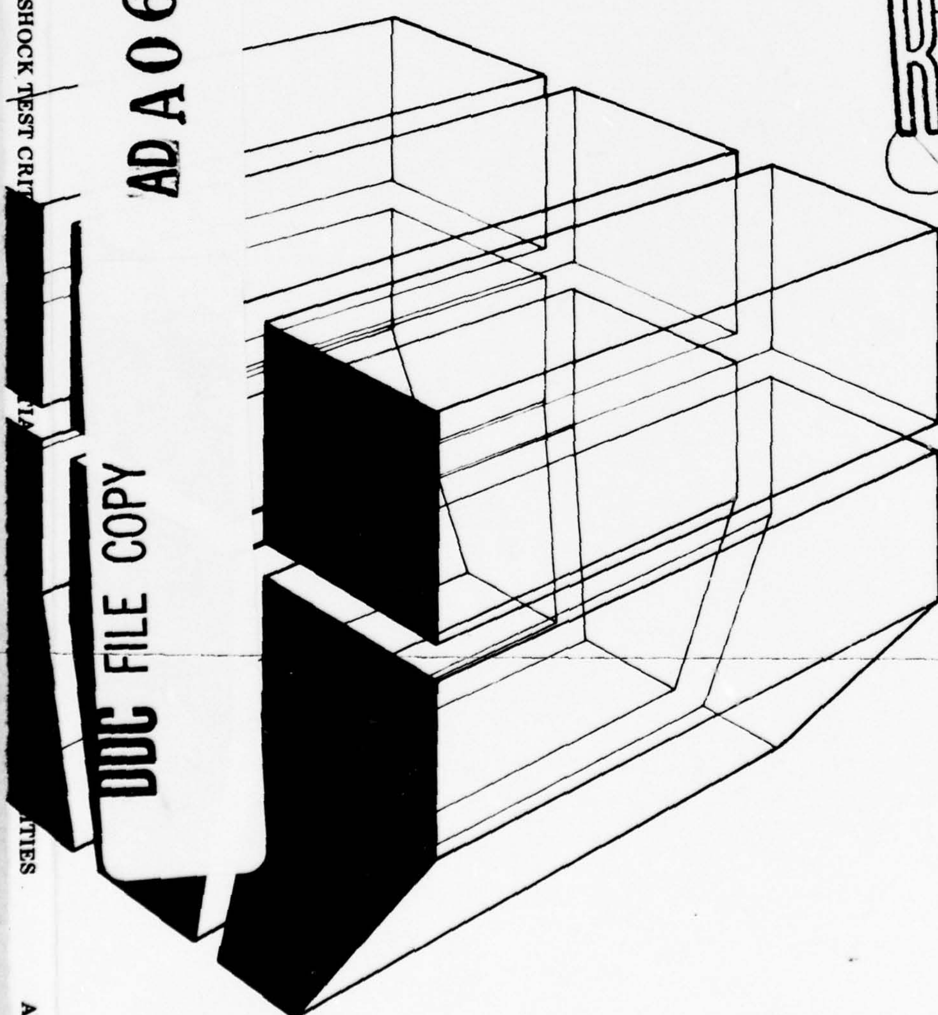
TECHNICAL REPORT M-236
April 1979
Earthquake Design Criteria for Interior Utility and Lifeline Systems

LEVEL

DEVELOPMENT AND USE OF SEISMIC SHOCK TEST CRITERIA FOR ESSENTIAL EQUIPMENT IN CRITICAL FACILITIES

by
P. N. Sonnenburg
J. D. Prendergast



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This report provides procedures for establishing seismic qualification test criteria for essential equipment in critical facilities and presents guidance for interpretation of the test results.

Since equipment representative of that used in the essential systems of critical facilities was observed to be closely related to many

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items of tactical support equipment used at missile sites, existing data from proof and fragility tests on tactical support equipment were reviewed to analyze failure characteristics. The failure data were organized so they could be statistically analyzed to provide estimates of the probability of failure.

The major tasks in the seismic test qualification of equipment are summarized; these tasks include test criteria formulation, test facility selection, test unit formulation, establishment of test qualification requirements, and interpretation of test results. Test criteria were developed by: (1) test axis selection, (2) statement of operating configuration, (3) definition of expected failure modes, and (4) description of the shock environment which can be transformed into a time history waveform to drive a shake table. Methods for developing waveform test criteria from the output of various types of dynamic building analyses are presented. Requirements for reporting and documenting test results are also discussed.

FOREWORD

This research was performed for the Directorate of Military Construction, Office of the Chief of Engineers (OCE), under Project 4A762731AT41, "Design, Construction, and Operations and Maintenance Technology for Military Facilities"; Task 04, "Construction Systems Technology"; Work Unit 002, "Earthquake Design Criteria for Interior Utility and Lifeline Systems." The applicable QCR number is 1.03.003. Mr. George Matsumura DAEN-MPE-B is the Technical Monitor.

The work was performed by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (CERL). Dr. P. N. Sonnenburg was the Principal Investigator for this project. Dr. G. R. Williamson is Chief of EM.

COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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SHOCK TEST CRITERIA FOR ESSENTIAL
EQUIPMENT IN CRITICAL FACILITIES

1 INTRODUCTION

Background

If critical facilities such as fire stations, communications centers, and hospitals are to provide post-earthquake emergency services, both the building structures and the utility and lifeline systems (essential equipment) which support functions most needed after the earthquake must survive. Because the 1971 San Fernando earthquake not only caused severe damage to the structure of the critical buildings but also to the essential equipment in each building, increased attention has been focused on earthquake-resistant design of equipment essential to providing post-earthquake emergency services. To date, this attention has been directed primarily toward hospital buildings and their associated essential equipment.

Assuming that a structure will survive, the major problem is to assure the functional integrity of all systems, subsystems, equipment, and components needed to support the essential functions. Table 1 lists the essential systems and equipment representative of hospitals. Requiring that all these systems and equipment items undergo seismic qualification testing is presently too costly and otherwise impractical. However, tests have been made to assess the hardness of related off-the-shelf equipment of tactical support equipment at missile sites.[1] In fact, the major contributions to the state of the art of testing equipment within buildings have resulted from the development of missile site and nuclear power plant facilities.

[1] F. E. Batchelder et al., Hardness Program Plan for SAFEGUARD Ground Facilities, Volumes 1 and 2, HNDDSP-73-153-ED-R (U.S. Army Corps of Engineers, Huntsville Division, 5 February 1974).

Table 1

Essential Systems for Hospitals*

1.[**] Fire protection system
    - Sprinkler system
        - Risers
        - Distribution mains
        - Valves
        - Support hangers
        - Bracing and clamps
    - Extinguishers
        - Receptacles
        - Mounting brackets
    - Standpipes
        - Mains
        - Risers
        - Clamps, hangers
2. Hazardous materials
    - Hazardous systems
        - Natural gas, O_2, N_2O
        - Risers
        - Distribution mains
        - Hangers
    - Hazardous storage
        - Radioactive storage
        - O_2 cylinders/storage tank
        - N_2O cylinders
        - Chemicals, reagents
        - Anesthetic gases
        - Fuel
3. Emergency power system
    - Transfer switches
    - Diesel-generator
        - Fuel piping
        - Cooling system
            - Cooling tower
            - Pumps
            - Piping
        - Batteries
        - Controls
    - Switchgear
    - Substation
    - Distribution panels
    - Motor control centers
    - Panel boards
    - OR and DR isolating panels
    - Conduits and bus
4. Communications
    - Telephone
    - Paging
    - Alarms
    - Radio

4. Communications (cont'd)
    - PA system
    - Nurses call
    - Interior systems
    - Program systems
5. Transport systems
    - Elevators
        - Rails
        - Counterweights
        - Motors
        - Generators
        - Controls
    - Dumbwaiters
6. Mechanical systems
    - Water pumps
        - Booster
        - Condensate
        - Condenser
    - Storage tanks
    - Compressors
        - Medical
        - Air control
    - Vacuum pump
    - Refrigerator compressors
    - Fans
        - Exhaust
        - Cooling tower
    - Chiller
    - Boiler
    - Controls
    - Heat Exchanger
    - Converters
    - Piping
        - Air
        - Vacuum
        - Water
        - Steam
        - Hangers
    - HVAC systems
        - OR and DR
        - ICU and recovery
        - Nursery
        - Ductwork
        - Air handling units
    - Maintenance/Repair shop
        - Equipment and tools
    - Maintenance/Repair stores and supplies
        - Maintenance/Repair parts
        - Housekeeping supplies
        - Emergency tools

7. Medical systems
    - Fixed
        - Autoclaves
        - X-ray
        - Film developers
        - Sequential multiple analyzer
        - Casework and exhaust hoods
    - Portable
        - Free standing or wheels
        - Dialysis units
        - Appliances
        - Laboratory/Medical equipment
        - Medical monitoring equipment
        - Beds, stretchers, carts, food service units
    - Medical stores and supplies
        - Drugs and medications
        - Chemicals
        - Instruments
        - Linens
        - General supplies
    - Medical records
8. Architectural systems
    - Lighting fixtures
        - Emergency lighting/batteries
        - Surgical
        - Personnel hazards
    - Stairwells
    - Doors/Egress
    - Glazing and fenestration
    - Ceilings
        - Egress corridors
        - OR, DR, emergency
    - Partitions and walls
    - Ornamentation
    - Office equipment
    - Storage racks, bins, lockers
    - Operation blocking hazards
9. Other equipment
    - Proximity to critical equipment
    - Expensive equipment
    - Non-emergency power
    - Sewer
    - Kitchen equipment
    - Laundry equipment

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* From *Task Report--Nonstructural Facility Systems*, R-7338-3311 (Agbabian Associates, April 1974).

** The nine essential systems shown are listed in order of relative priority. For example, elevators (under Transport Systems) cannot function without emergency power. Likewise, since the operation of medical equipment is highly dependent on other systems being operational, medical systems rank seventh in priority.

The test results analyzed for this report were obtained from equipment tested for use at missile sites. Derivations for test criteria were taken primarily from nuclear facility literature. Buildings in both categories have generally been treated as elastic structures, with the difference being in the definition of the shock environment. The assumption of structural elasticity considerably simplifies the task of generating equipment test criteria, and the required method is mostly interchangeable. However, other critical facilities, such as hospitals, are purposely designed to behave inelastically during strong ground motions. At present, experience in developing test criteria for equipment in inelastic structures is limited.

Rigorous theoretical and analytical procedures for generating test criteria for equipment in inelastic structures can be derived, but these procedures are relatively costly and are presently restricted to academic studies. The general lack of building floor response data, in particular for structural motion in the inelastic range, dictates that conservative approximations be made in establishing test criteria for equipment.

Purpose

The purpose of this study is (1) to formulate procedures for establishing test criteria for seismic qualification of essential equipment in critical facilities (including those designed to behave inelastically) by proof testing and fragility testing, and (2) to provide guidance for interpretation of test results.

Approach

In the first phase of the study, the results of the SAFEGUARD tactical support equipment (SG/TSE) program were reviewed, since the equipment tested in the SG/TSE program was similar to the essential equipment of interest. The appendix lists the test units, significant test information, and results. However, since the shock environment

was not the same as that expected from an earthquake, the SG/TSE results were viewed qualitatively rather than quantitatively.

Applicable information from the SG/TSE program was then used to establish a rationale for the interpretation of failure data from testing. Chapter 2 discusses this second phase, which involved demonstrating how the raw failure data can be rendered amenable to some practical method of analysis.

The third phase was devoted to identifying the major tasks in the seismic qualification procedure. These tasks are also discussed in Chapter 2.

These three phases provided the framework of problem definition and test result interpretation used to develop recommended standard definitions (Chapter 3) in the final phase of the study. This final phase also involved developing (1) the method for establishing test criteria based on a review of existing literature on the subject (Chapter 4), and (2) the requirements for documenting results (Chapter 5).

Scope

Three methods can be used to qualify essential equipment for installation in critical facilities: (1) mathematical analysis, (2) testing, and (3) a combination of testing and analysis.[2] This study addresses only qualification by testing, but the procedures are also applicable when analysis is used with testing. Although the earthquake shock environment is of primary concern, the procedures can be applied to any form of shock environment, such as nuclear blast, and to essential equipment in critical Army facilities. It is assumed that a dynamic analysis of the critical facility has been performed and the results of the building analysis are available, including the building's

[2] Structural Analysis and Design of Nuclear Plant Facilities, Draft Trial Use and Comment (Committee on Nuclear Structures and Materials of the Structural Division of the American Society of Civil Engineers [ASCE], 1976); C. W. Roberts and G. D. Shipway, "Seismic Qualification--Philosophy and Methods," Journal of the Power Division, ASCE (January 1976).

natural frequencies, mode shapes, participation factors, and design spectrum or floor motion time histories. It is also assumed that a dynamic analysis of the equipment has not been performed, and therefore these same properties for the equipment are unknown. Information about the equipment is assumed to be limited to basic physical properties (i.e., weight, dimensions, mounting conditions, etc.) and sufficient data to estimate a damping ratio. Finally, it is assumed that the equipment can be adequately represented by the response of a single-degree-of-freedom linear system.

Mode of Technology Transfer

The results of this study will be incorporated into a new technical manual in the TM 5-809 series. The study will also impact on MIL-STD-831, Preparation of Test Reports (28 August 1963).

2 SEISMIC TEST QUALIFICATION PROCESS

Review and Analysis of the SG/TSE Test Results

The appendix lists pertinent test information and failure data for the SG/TSE program. Comparison of the typical equipment needed to support the nine essential systems identified for hospitals (Table 1) with the equipment listed in the appendix emphasizes the direct relationship between the TSE and essential equipment of concern in this study.

The major difference between the TSE test program and a suitable program for essential equipment is the frequency content of the expected shock environment. The TSE program was designed to assess equipment hardness against nuclear blasts, while earthquake shock conditions will prevail for essential equipment of concern in this study. Figure 1 shows a composite envelope of many floor shock response spectra actually used in the SG/TSE program. Also shown is a typical ground shock response spectrum, normalized to a peak acceleration of 1.0 g, which could be used to develop floor spectra at specific locations within a building. The figure shows that the frequency content of the ground spectrum is generally lower than that for the TSE floor spectra envelope. This difference renders the TSE shock environment more severe at frequencies above 4.0 Hz and less severe below 4.0 Hz. Therefore, the TSE test results are not applicable to the essential equipment of critical facilities. The TSE testing experience is still valuable, however, in generalizing conclusions which will be helpful as guidance in future test projects for essential equipment.

The failure data from the SG/TSE are interpreted in the appendix. The majority of these tests were proof tests, the simplest type of fragility testing. Proof tests subject the unit to a few (e.g., four or six) test levels of increasing severity until the full expected environmental test level is reached. A class of electrical equipment (motor control centers) was submitted to partial fragility testing, in

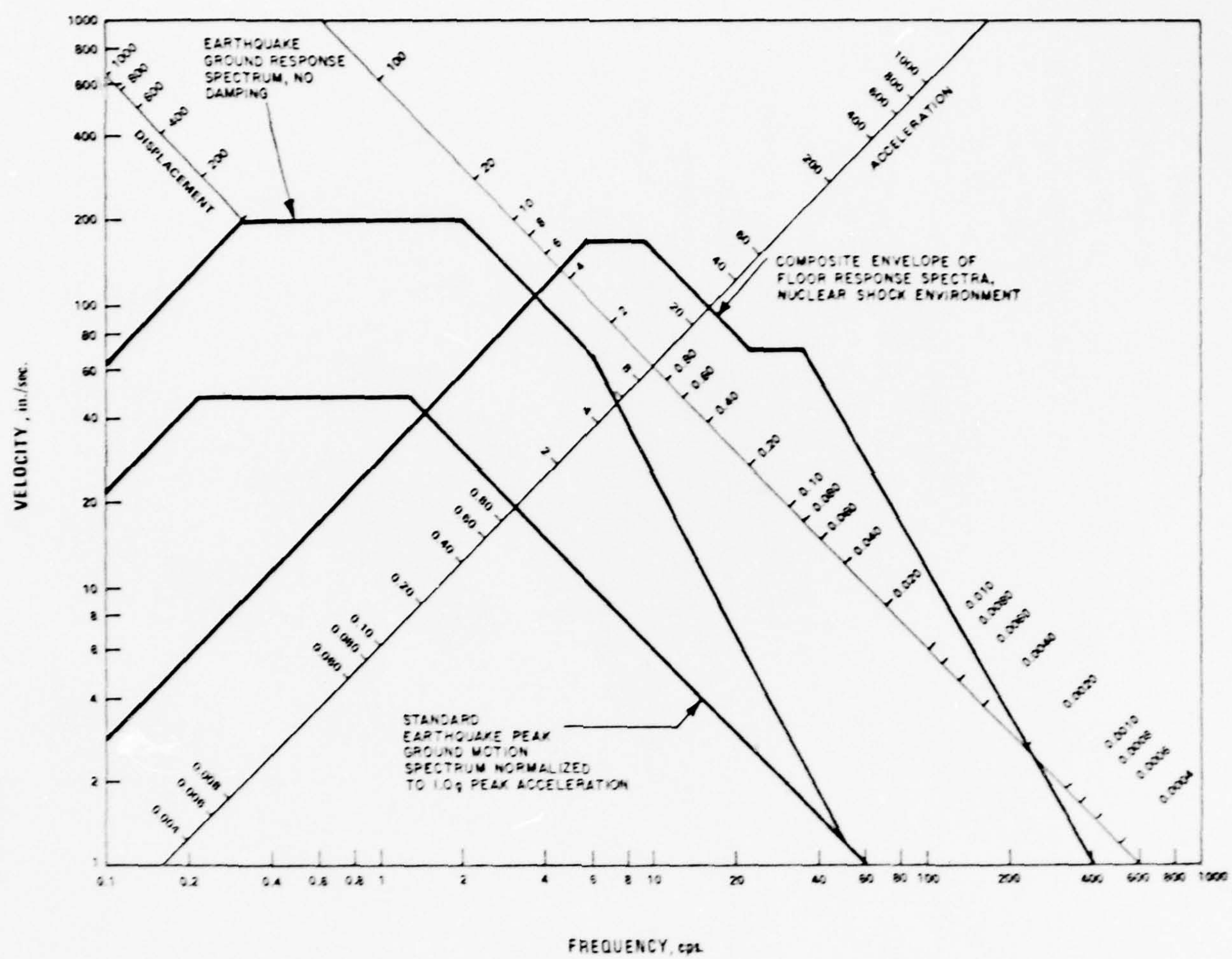

Figure 1. Comparison of earthquake and nuclear blast shock spectra.
SI conversion factor: 1 in. = 25.4 mm.

which an average of 11 tests was held in each of three orthogonal directions for each test unit. Only one class of equipment (relays) was submitted to full fragility testing.

Analysis of the TSE failure data shows that failures could usually be identified by two properties: (1) functional performance, and (2) expected consistency (see Figure 2). Functional performance failure could be further classified as qualifying or lingering, depending on the significance of the failure in causing functional downtime. Expected consistency failure could be classified as consistent or independent, according to the predictability of the failure at a given test level. Therefore, based on the TSE failure information, these failure classifications are recommended for use in analyzing test results. Formal definitions are suggested in Chapter 3.

The appendix shows the typical failure modes observed in the TSE test results. Generally, the same types of failures may be expected from testing essential equipment, even though the frequency content of earthquake ground motion is lower than that of the TSE nuclear blast environment. The list of expected failures should be useful to equipment designers and test engineers in future hardness assessment and assurance projects.

Identification of Major Tasks

Figure 3 is a flow chart of five basic tasks to be considered successively during the test qualification procedure:

1. Formulation of test criteria
2. Selection of test facilities
3. Formulation of test units
4. Establishment of test qualification requirements
5. Interpretation of test results.

Test Criteria Formulation

Four primary subtasks are required to establish test criteria:

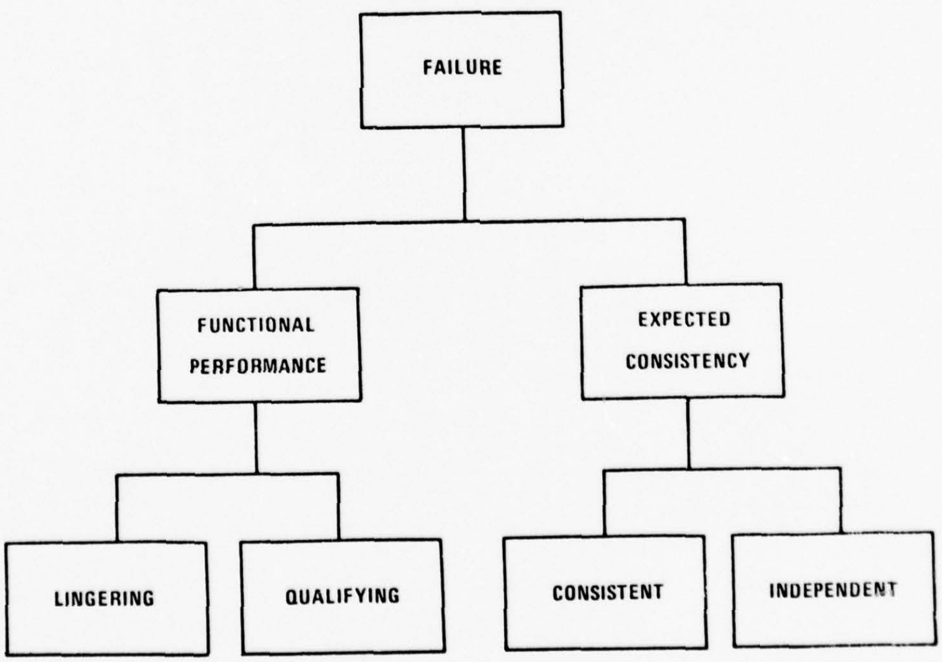

Figure 2. Failure Classifications.

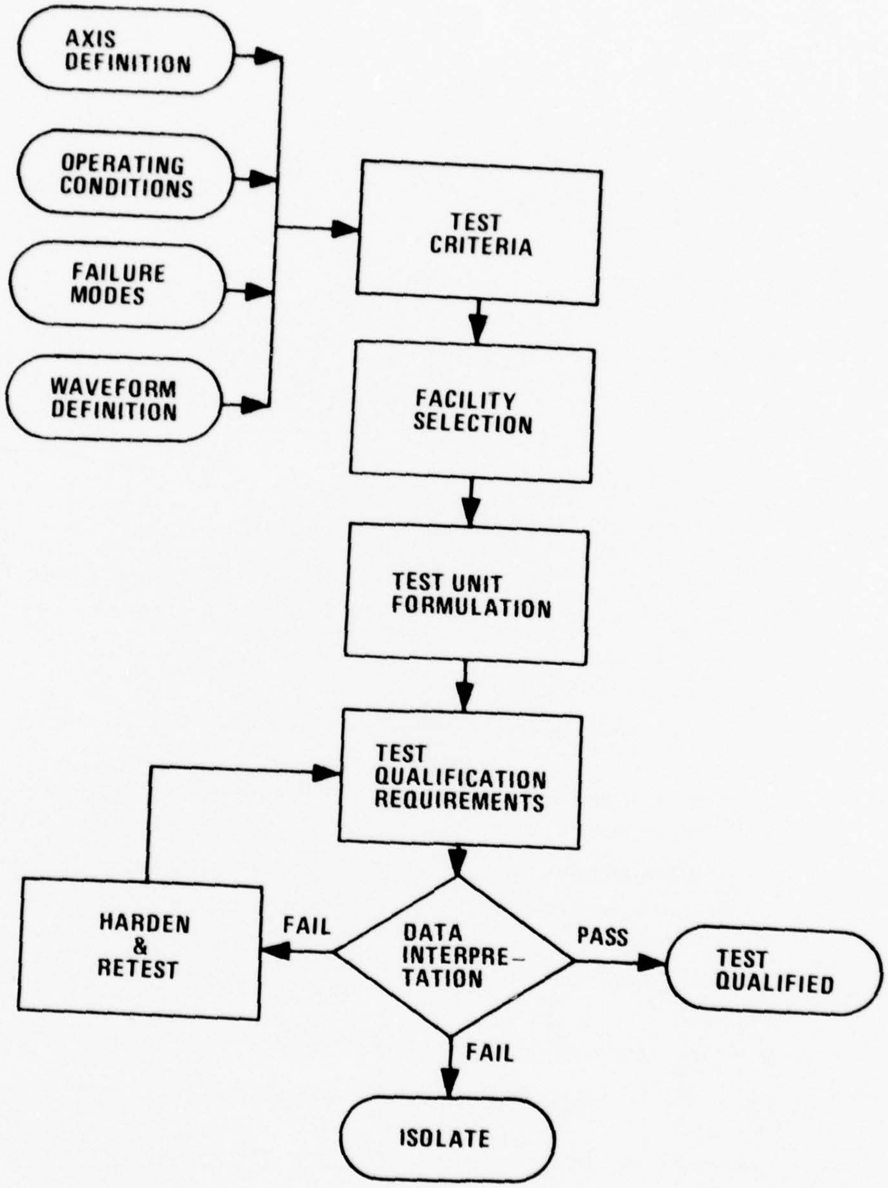

Figure 3. Stages of test qualification.

1. Selection of test axes

2. Statement of required operating conditions during testing

3. Definition of what constitutes failure of the equipment

4. Determination of the information required to generate a time history waveform for driving a shake table.

Selection of test axes for a particular item of equipment depends on the location and orientation of the equipment. Single- or multiple-axis tests may be necessary. If many identical items are located throughout a building and mounting standards do not restrict orientation, testing in simultaneous axes may be warranted. On the other hand, an item which is mounted at a specific location in a specific orientation should be tested in that configuration. The possibility of significant coupling effects (i.e., motion in one direction exciting equipment response in a different direction) must also be considered in specifying single- or multiple-axis testing.[3] References discussing coupling effects and the selection of test axes are available.[4]

The equipment should be tested in the condition in which it is expected to be operating during an earthquake. For example, since an air conditioning unit may normally be operating when an earthquake occurs, it should be tested in its normal running condition. However, an emergency generator may be in its functional condition for only 30 minutes per week. Thus it may be safe to assume that the generator is normally shut down during an earthquake. It can therefore be tested in the shut-down condition and then started following the test to evaluate

[3] Structural Analysis and Design of Nuclear Plant Facilities, Draft Trial Use and Comment (Committee on Nuclear Structures and Materials of the Structural Division of ASCE, 1976).

[4] IEEE Recommended Practices for Seismic Qualification of Class IE Equipment for Nuclear Power Generating Stations, IEEE 344-1975 (Institute of Electrical and Electronics Engineers [IEEE], 1975); Skreiner K. M., et al., "New Seismic Requirements for Class I Electrical Equipment," IEEE Transactions, Paper T 74 048-5 (IEEE, 14 November 1973).

its functional integrity. This portion of the test criteria must be developed on a case-by-case basis and is beyond the scope of this report.

Detailed information must be used to define what constitutes failure of the test unit in general and the components of equipment in particular. The detrimental effects of failure on interfacing equipment must also be determined. It is often found, for example, that a relay will chatter or trip under the test environment. The unit itself could be rendered functional simply by resetting the relay or eliminating the severe shock environment. However, this type of failure often causes interfacing systems to fail immediately because electrical control is lost. Merely resetting the relay or eliminating the shock may not return the interfacing equipment to its functional state. Hence, such a relay failure would constitute functional failure of the interfacing equipment. Again, such test criteria must be determined on a case-by-case basis and cannot be addressed in this report.

One practical problem that arises when attempting to establish test criteria for equipment qualification is the selection of the waveform for simulating the earthquake environment the equipment may experience. Assuming that the earthquake environment is given in the form of a response spectrum, it is important to recognize that the response spectrum does not specify either the duration of the environment or its exact waveform. Therefore, additional criteria concerning the desirable characteristics of the waveform are needed. Roberts and Shipway[5] provide an excellent summary of waveform requirements:

> There are two general types of waveforms, as shown in Figure [4]. The characteristic of single frequency waveforms is that each frequency in the spectrum is applied to the device individually. The characteristic of multiple frequency waveforms is that several frequencies in the spectrum are applied to the device simultaneously, or almost simultaneously. Table [2] summarizes the waveforms best suited for the various test applications.

[5] C. W. Roberts and G. D. Shipway, "Seismic Qualification--Philosophy and Methods," Journal of the Power Division, ASCE (January 1976).

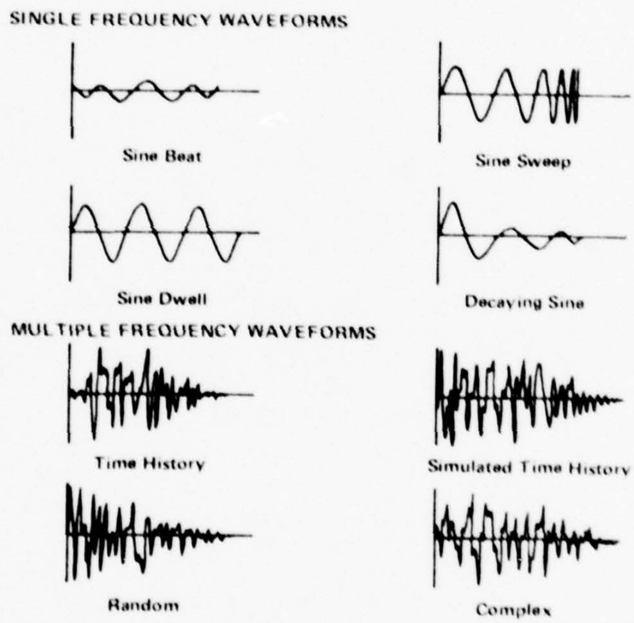

Figure 4. Waveform types. Reprinted by permission of the American Society of Civil Engineers from C. W. Roberts and G. D. Shipway, "Seismic Qualification--Philosophy and Methods," Journal of the Power Division, ASCE (January 1976).

Table 2

Waveform Decision Summary*

Application (1)	Type of Test: Single Frequency Waveform: Sine beat (2)	Sine sweep (3)	Sine dwell (4)	Decaying sine (5)	Multiple Frequency Waveform: Time history--real (6)	Time history--synthesized (7)	Random (8)	Complex (9)
Proof testing (narrow band)	✓			✓				
Proof testing (broad band)						✓	✓	✓
Fragility testing**	✓		✓					✓

* Reprinted by permission of the American Society of Civil Engineers from C. W. Roberts and G. D. Shipway, "Seismic Qualification--Philosophy and Methods," Journal of the Power Division, ASCE (January 1976).

** All checked waveforms should be used.

The sine beat or decaying sine waveform should be utilized for proof tests where the required shock response spectrum is narrow band, i.e., the entire spectrum can be enveloped by a single sine beat or a single decaying sine waveform. A multiple frequency waveform (synthesized time history, random, or complex) should be utilized for proof testing in cases where the required shock response spectrum is broad band. There may be hybrid situations partway between a narrow band spectrum and a broad band spectrum which require some composite of a single frequency waveform and a multiple frequency waveform (e.g., a sine beat superimposed on random). In any case, the major criterion to keep in mind in selecting the waveform for proof testing is that the waveform should be as close a simulation of the actual environment as is practical.

Additionally, no matter which waveform is used, the actual motion created at the test table should be analyzed and a test response spectrum produced (Figure [5]). This spectrum should then be compared to the required response spectrum in order to verify that the test motion has adequately enveloped the required qualification environment. Either single frequency or multiple frequency tests may be required, or both. Single frequency tests usually are specified as either steady-state sinusoidal or sine beat tests. This type of testing should be required if the floor excitation is expected to contain relatively strong sinusoidal motions at discrete frequencies. Multiple frequency tests are generally more appropriate if discrete frequencies cannot be identified in the floor motion.

Random motion or complex waveforms whould be specified when multiple-frequency tests are required. For either single- or multiple-frequency testing, a shaped spectrum can be used to define the frequency content and amplitude of the environment. It is recommended that the term "test level" (see Chapter 3) be used when referring to the shaped spectrum required for specifying the waveform test criteria. For a more complete discussion, see Chapter 4.

Test Facility Selection

Only a few test facilities are available to the Army for seismic equipment qualification. Selection of the appropriate test facility for a particular item of equipment must be based on the physical properties of the item and the test criteria established above. If a facility which can provide the required test criteria cannot be found, the facility which can most closely approximate the criteria must be selected.

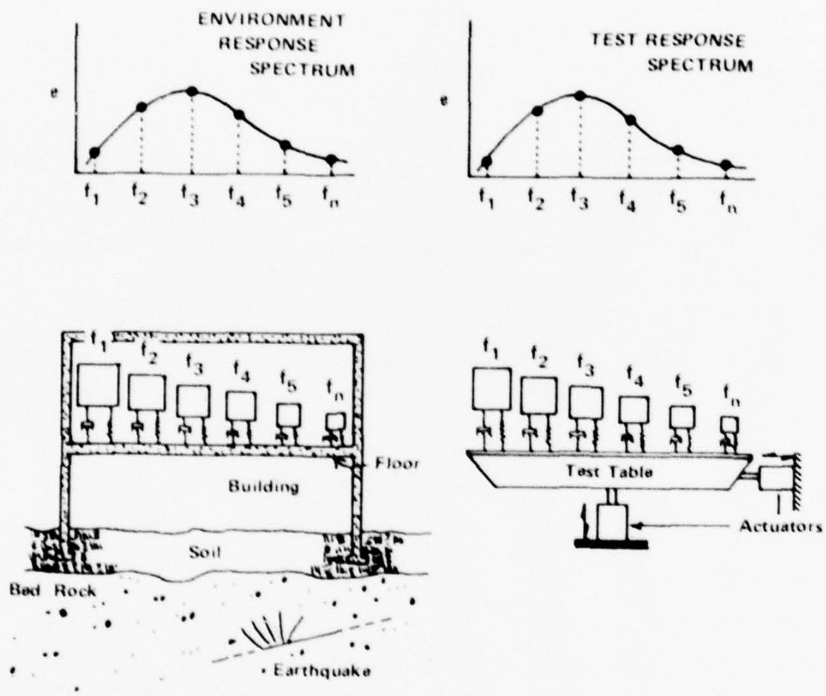

Figure 5. Testing to shock response spectrum. Reprinted by permission of the American Society of Civil Engineers from C. W. Roberts and G. D. Shipway, "Seismic Qualification--Philosophy and Methods," Journal of the Power Division, ASCE (January 1976).

Test Unit Formulation

If a test facility's loading capacity is sufficient, assemblies of related equipment may be tested simultaneously. A "test unit" (see Chapter 3) consists of a single item of equipment or any suitable combination of equipment items which may be simultaneously subjected to a single test environment. Test units are economic and allow testing on a subsystem or system level, when appropriate.

Test Qualification Requirements

Existing fragility test reports indicate that testing tends to be conducted in three degrees of sophistication, according to the number of tests and waveform definitions considered necessary to establish sufficient failure data.[6] Most units are proof tested. Certain other units require partial fragility testing. Full fragility testing, however, is restricted to very few units, since hundreds of tests may be required for each unit.

Proof testing involves testing a unit at a few (i.e., four or six) progressively increasing levels of severity until the full level of the expected dynamic environment is reached. Go/no-go results are expected; that is, either the unit survives the full environment, or it fails and must be hardened by redesign. The use of a few progressively increasing test levels prevents the unit from being completely demolished before the failures can be investigated. Proof testing is therefore an expedient method of discovering failures which are highly likely to occur at or below the expected shock environment level. These failures are termed "consistent" (see Chapter 3), since for all practical purposes they can be predicted with 100 percent assurance.

Experience shows that certain types of equipment exhibit intermittent or erratic failures, typically caused by electrical relay chattering or circuit breaker tripping. These failures are termed "independent," since they have the properties of an independent random variable

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6 Subsystems Hardness Assurance Analysis, HNDSP-73-161-ED-R (U.S. Army Corps of Engineers, Huntsville Division, December 1974).

as defined in mathematical statistics. If independent failures are encountered, the unit may have to be rescheduled for partial or full fragility testing.

Initially, all essential equipment which cannot or should not be qualified by analysis should be scheduled for proof testing. Past experience (see the appendix) indicates that a large percentage of items may survive proof testing and therefore may be considered test-qualified.

Partial fragility testing should be scheduled for units or items of equipment which exhibit independent failures during proof testing which cannot be immediately corrected by redesign. Twenty or more tests are often required to allow a rough estimate of the probability of failure and to determine the fragility envelope for test levels at or below the full environment level. U.S. Army Construction Engineering Research Laboratory (CERL) Special Report M-209[7] gives the method for estimating the probability of failure and examples of its use.

In cases where hardening the test unit or equipment is not practical, the estimated probability of failure can be used to determine the required action. The results of partial fragility testing will indicate those units which may be considered test-qualified with an acceptable probability of failure. Time and funding constraints may require that some units be subjectively judged as acceptable at this stage. In practice, only critical items can be scheduled for further testing.

Units which require full fragility testing do not have to be subjected to proof or partial testing if the unit's essential or critical nature warrants and if the occurrence of either consistent or independent failures is deemed sufficiently probable based on past experience with similar equipment. Full fragility testing may require hundreds of tests in narrow frequency bands, in different axes, and

[7] P. N. Sonnenburg, Fragility Data Analysis and Testing Guidelines for Essential Equipment in Critical Facilities, Special Report M-209/ADA038768 (U.S. Army Construction Engineering Research Laboratory [CERL], March 1977).

at many test levels. The objective of full fragility testing is to identify and correct as many failures (see Chapter 3) as possible, so that the probability of failure can be minimized. Test levels may exceed the full expected environment level if the results from such tests will provide insight helpful in correcting defects or will improve confidence in the probability of failure estimate. If the defect cannot be sufficiently hardened to reduce the probability of failure to an acceptable level, the unit must be isolated from the environment. In this event, the objective of the full fragility testing is to establish a fragility envelope, with confidence limits, for direct use by isolation system designers.

Interpretation of Failure Results

When a significant failure occurs, there are three possible courses of action (see Figure 3). First, the equipment may be hardened by redesign and repair and then retested. Second, depending on the nature of the failures, the probability of failure may be estimated. If the probability of failure is acceptable, the equipment may be judged as qualified. This course of action may require partial or full fragility testing. Generally, sufficient failure information cannot be obtained from a proof test to estimate the probability of failure with sufficient accuracy. Third, the equipment may be isolated from the environment.

When consistent failures occur during fragility testing, the course of action to be taken by the test engineer or equipment designer is usually clear. For example, in a proof test, a consistent failure means 100 percent probability of failure below the test level. The engineer may not be able to continue testing at higher levels until the failure is corrected by redesign, i.e., hardening the unit to assure functional survivability. A suitable alternative may be to condone the failure temporarily if it does not affect other possible modes of failure during testing. Also, in cases where consistent failures occur below the 100 percent proof test level, the prediction of the same failure is 100 percent assured, and hence is not a matter of probability. The fragility envelope can be clearly defined in this case.

When independent failures occur, the possible courses of action are not well defined. The prediction of failure becomes a matter of probability. Because a literature search revealed that no theoretical treatment of the statistical analysis of fragility data was readily available for reference by test engineers, designers, or manufacturers, a rigorous mathematical method of calculating the probability of failure from fragility data was developed and documented in CERL Special Report M-209. Results presented in that report for applications of the theory to hypothetical test results and to the partial fragility test results from the SG/TSE program should be useful in managing test programs. The estimation of the number of tests at various test levels required to achieve a desired accuracy (or confidence) in predicting probability of failure of a unit should aid in planning test schedules.

Although fragility, fatigue, and strength testing are all usually classified as destructive test methods, there is much more readily available literature addressing the statistical analysis of strength and fatigue data than there is addressing fragility data, probably because strength and fatigue data are generally more amenable to analysis than fragility data. However, differentiating between the meaning of fragility test results on one hand and strength of fatigue results on the other is important. Since this report focuses on the interpretation of fragility data, a brief comparison of the meaning of test results is in order. A more complete discussion is given in CERL Special Report M-209.

All three forms of testing mentioned above are statistical experiments. Mathematically, a statistical experiment can be divided into two parts: input and outcome. The input criteria are completely defined and controlled (within limits of accuracy) by the investigator. The outcome, or test result, may or may not be random in nature and is not controllable by the investigator except through variation of the input parameters.

In a simple strength test, for example, a specimen might be loaded in tension until failure occurs. The engineer controls the specimen

geometry, physical properties, and the loading rate. Hence this information comprises the input data. When failure occurs, the corresponding load is recorded; i.e., the statistical outcome is the load at which failure occurred. Note that failure must occur before the outcome is recorded. When many nominally identical specimens have been tested, the failure loads may be arranged in the form of a probability density function. The mean failure load can then be estimated, as can central statistical moments, which may be used to predict the probability of failure (with confidence limits) of such specimens at any prescribed load level. A parallel discussion can be provided for fatigue testing (see CERL Special Report M-209).

In a proof test (a simple fragility test), the specimen is subjected to a test level predetermined by the engineer. Parameters used to define the load therefore comprise input data. In contrast to the strength test example above, failure may not occur. The outcome in this case is either survival or failure at the prescribed test level. If failure occurs, all that is known is that the same failure could have occurred at any test level less than or equal to the actual test level. Therefore, fragility failure data must be displayed in the form of a probability distribution function (see CERL Special Report M-209), instead of the density function representation appropriate for strength test data. In analyzing fragility data, the test level must be regarded only as an upper bound of failure when failure occurs.

Fragility testing is closely related to sensitivity testing of explosives, which is discussed in several publications.[8] The detonation

[8] T. W. Anderson, P. J. McCarthy, and J. W. Tukey, Staircase Methods of Sensitivity Testing, NAVORD Report 65-46 (Navy Department, Bureau of Ordnance [NAVORD], 21 March 1946); Statistical Analysis for a New Procedure in Sensitivity Experiments, AMP Report No. 101.1R, SRG-P No. 40 (Statistical Research Group, Princeton University, July 1944); A. Bullfinch, Improved Methods and Techniques for Testing Impact Sensitivity of Explosives, Technical Report 2282 (Picatinny Arsenal, July 1956); "Method of Computing Impact Safe Distance for MIL-STD-313," Journal of the Joint Army Navy Air Force (JANAF) Fuze Committee, Serial No. 32 (JANAF, 10 September 1964); L. D. Hampton, Fundamental Statistical Ideas as Related to Explosive Sensitivity Tests, NAVORD Report 4379 (U.S. Naval Ordnance Laboratory, 14 September 1956).

of an explosive charge is primarily a function of impact shock, where the variable of concern may be pressure. It is found that detonation (failure) does not always occur at a precise shock level. There is a probability that this outcome will occur at any shock level less than or equal to the actual test shock level. Therefore, the mathematics required to analyze explosive sensitivity is essentially the same as that required for fragility data.

3 RECOMMENDED DEFINITIONS

This chapter presents definitions which will aid in improving communications between activities involved in fragility testing. The definitions are based primarily on an analysis of failure data contained in the Army Corps of Engineers Huntsville Division documentation on SAFEGUARD systems testing.[9]

Test Unit: A unit is defined as any system, subsystem, component, or combination thereof which may be treated independently, either as an assembly or as a detailed part with a specific function. For example, individual valves in a piping system may be sufficiently rugged to avoid testing each one. Since the weakest points may be the joints between the valves and the piping, testing or analyzing the entire piping system as a unit may be desirable. The size of a test unit is limited by its capability of being subjected to a single defined shock environment; i.e., a piping system of a building would be too large to test as one unit.

Fragility: A unit's fragility is defined by stating the value of a variable, such as acceleration, at which it will fail.

Fragility Envelope: A fragility envelope is defined by expressing the variable describing failure as a function of frequency.

Hardness: A unit's hardness is defined as its probability of failure under expected environmental loading conditions.

Hardness Assessment: Assessment of a unit's hardness is achieved by calculating the unit's probability of failure under (possibly numerous) specified shock loading conditions.

Hardness Assurance: Assurance of hardness is achieved by reducing the probability of a unit's failure below an acceptable value. This reduction can be accomplished by redesigning the unit to eliminate failures under a prescribed shock environment, or by isolating the unit from the prescribed shock environment.

[9] Subsystems Hardness Assurance Analysis, HNDSP-73-161-ED-R (U.S. Army Corps of Engineers, Huntsville Division, December 1974).

Test Level: The shock environment for fragility testing is usually defined as a shaped shock spectrum, referred to as the 100 percent level. Tests may be conducted with the same spectrum shape, but with a uniform amplitude change in parameters. The level of the test refers to the amplitude of a single parameter such as displacement, velocity, or acceleration, which can be used for comparison with the 100 percent level. The same terminology is used for application to any type of shock environment.

Failure: A failure is defined as any malfunction or degradation of performance or structural integrity of an item of equipment. A change in performance which causes any interfacing equipment to fail is also considered a failure, even though the change may not be detrimental to the parent equipment.

Consistent Failure: When a failure occurs repeatedly and can be predicted as a well-defined test level value, the failure is said to be consistent. A unit will exhibit 100 percent probability of failure at test levels at or above this well-defined level, and the failure will be caused by the same (consistent) defect. Numerous consistent failures may occur simultaneously. A fragility envelope can be formed if failures are consistent. For example, a mounting bracket which will buckle at a reasonably precise load (i.e., test level) for every similar item of equipment should be considered as a consistent failure. Consistent failures have been observed to occur mostly, but not always, in equipment structures.

Independent Failure: When a failure occurs erratically, at different levels of the variables, it is said to be independent. A well-defined fragility envelope cannot be formed from failure levels if the failures are independent. When this situation occurs, the probability of a failure of a unit at any test level must be considered. Independent failures have usually, but not always, occurred in electronic and electrical components. For example, in a bank of nominally identical circuit breakers, several may open under a specific test level. If these breakers are closed and the test repeated, the same breakers may remain closed while others open. For practical purposes, the opening of a specific breaker may then be

considered as statistically independent, with a probability of failure something less than 100 percent under the prescribed test level.

Qualifying Failure: A qualifying failure is one which can be corrected almost immediately, or which has a degrading influence not directly affecting the unit's function or that of any other interfacing unit. For example, a cabinet door latch or fastener may open, which will have no immediate effect on the performance of the internal equipment. The failure may degrade the structural integrity of the item slightly, but there may be no need to redesign the fastener mechanism to withstand the shock environment.

Lingering Failure: A lingering failure is one which requires an intolerable time delay to correct. The failure may occur directly within the test unit, or faulty output by the unit may cause an interfacing system to malfunction. For example, if water pressure in a pipe line drops momentarily under the shock environment, it may cause an essential pump to shut down. If the delivery of water is critical in this case, and if an intolerable delay is required to restart the pump, then the failure should be classified as lingering. In every case where a lingering failure is identified, an attempt should be made to eliminate or significantly reduce the probability of failure.

Floor Response Spectrum: A floor response spectrum is a shock spectrum calculated from the absolute floor time history. A floor response spectrum is a plot of the maximum responses of single-degree-of-freedom oscillators attached to the floor. Equipment damping is a variable parameter. The floor response spectrum is related to equipment vibration in the same manner that the ground response spectrum is related to building vibration.

Proof Testing: Proof testing is the simplest type of fragility testing and is used to qualify equipment for a particular application or requirement. Typically, a test unit is subjected to a few (i.e., four or six) test levels of increasing severity, until the full expected environmental test level is reached. Go/no-go decisions may be made for most equipment, based on proof test results. Proof testing is an expedient method of identifying consistent failures.

Partial Fragility Testing: Partial fragility testing may be required if independent failures result or are suspected from proof testing. It is not unusual for 20 or more tests to be held in different axes to help identify and possibly correct the independent failures. For failure which cannot be eliminated, the probability of failure can be estimated roughly.

Full Fragility Testing: Full fragility testing may be required for highly critical and sensitive equipment in which numerous independent failures may occur. Several hundred tests may be necessary. The test levels may be defined in terms of stationary, nonstationary, narrow band, or broad band random properties. In particular, sine beat, continuous sine, and sweep sine tests are often used. Results of full fragility tests conducted, where possible, after failures have been corrected can be used to establish a mean fragility envelope with statistical confidence bands. This information may be used either as design criteria for an isolation system, or to provide an estimate of the probability of failure of the test unit under the expected environmental conditions. The accuracy of estimation of the mean fragility envelope or the probability of failure is a function of the number of tests conducted.

4 DEVELOPMENT OF EQUIPMENT WAVEFORM TEST CRITERIA

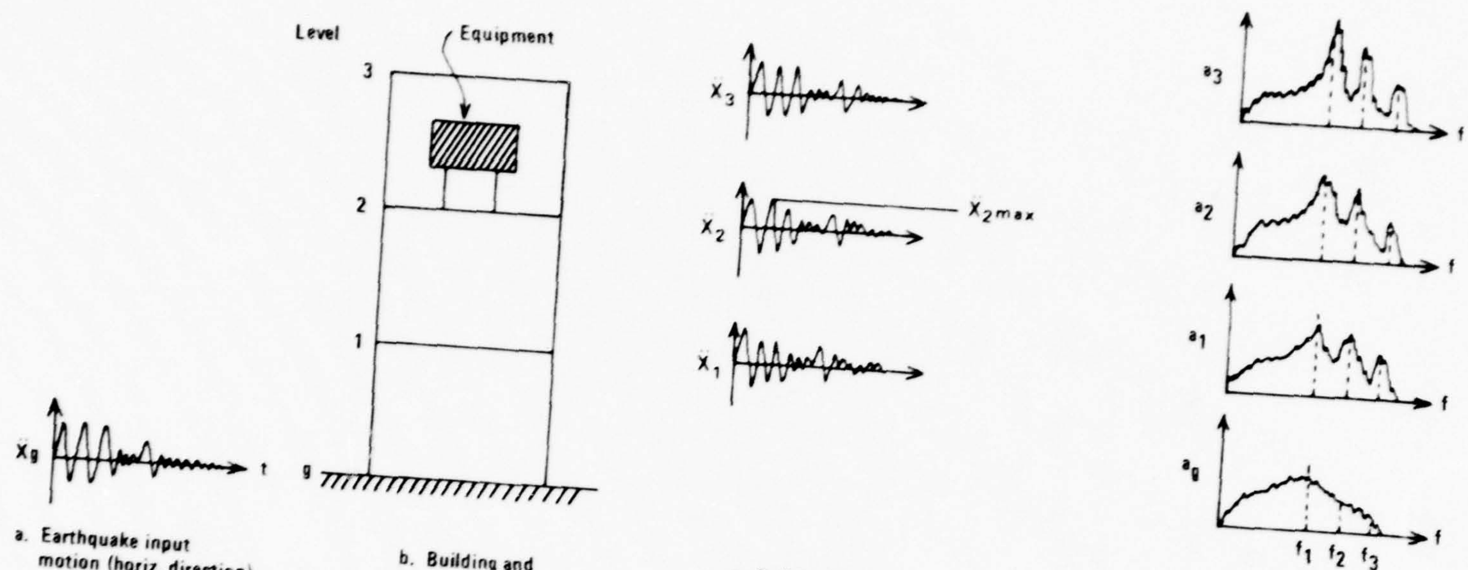
General

The principal objective of seismic qualification testing is to demonstrate that essential equipment functions properly during and after an earthquake. Consideration must be given to both the functional and structural characteristics of the equipment. Certain items of equipment can be subjected to seismic qualification tests while simulating the operating conditions and monitoring performance during the test, thereby verifying simultaneously the functional and structural integrity of the equipment. In the case of large and complex equipment, such as elevator systems, simulation of the operating conditions may be impractical, and alternate criteria must be developed to assure the functional integrity of the equipment. The development of these criteria must be done on a case-by-case basis and is beyond the scope of this report.

In concept, it is possible to develop both structural and functional test criteria for every type of equipment of concern. If the equipment cannot be tested, the criteria should be used for design purposes. For example, most types of equipment have some form of structural support. The test (or design) criteria can be used to design the supporting system even though the structural and functional integrity of the equipment cannot be verified by testing. The method reflecting the state of the art in developing waveform test criteria is provided in the following sections.

Development of Seismic Input for Essential Equipment

Figure 6 illustrates the seismic response of a building and the general effects of this response on equipment in the building. The earthquake input motions, building and equipment, and building response are shown in Figures 6a, b, and c, respectively. If the floor level



a. Earthquake input motion (horiz. direction).

b. Building and equipment.

c. Building's response to earthquake.

d. Acceleration response spectra at floor levels.

Figure 6. Building and equipment response.

motions are used to calculate response spectra at these levels, spectra of the form shown in Figure 6d are produced. These spectra exhibit peaks of high amplifications in the regions of the natural frequencies of the building. Thus, if the natural frequencies of the supported equipment are in the same range, high response and corresponding structural and functional failures may result. The problem of formulating test criteria for essential equipment is therefore one of obtaining an appropriate time history of the motions at the base of the equipment and/or calculating or developing a suitable approximation of floor response spectra.

Conceptually the problem is straightforward, but computationally the task is formidable. It is therefore worthwhile to briefly describe the dynamic analysis methods for calculating the seismic response of buildings and to discuss some of the assumptions used in the seismic analyses of equipment. The most widely used methods for calculating the response of buildings and equipment are the response spectrum and time history modal analysis methods. An alternate method for claculating the time history response of buildings having nonlinear structural properties is the direct step-by-step numerical integration of the coupled equations of motions. It should be noted that both of the modal analysis methods are applicable only to linearly elastic structures. Moreover, designing buildings to resist severe seismic motions without allowing minor to moderate amounts of inelastic behavior (i.e., ductility factors of 1.5 to 5) is generally recognized as impractical. Procedures have been developed for modifying the elastic response spectrum to incorporate a rational representation of the effects of inelastic behavior in buildings. A similar simplification for accommodating the effects of inelastic behavior in the time history modal analysis method currently is not available. Consequently, direct step-by-step numerical integration of the equations of motion is the only feasible method for rigorous solution of the nonlinear response of buildings. The nonlinear dynamics problem is significantly more difficult than the linear problem because, in the most general case, the stiffness and damping matrices

must be regenerated at each time step, thus greatly increasing the computational efforts.

The general principles of the response spectrum method can be described with the aid of the idealized building and analytical model shown in Figure 7a. First, the natural frequencies and corresponding mode shapes are calculated from the structural properties of the building (Figure 7b). Modal participation factors are then calculated using the relationship in Figure 7c. The next step is to determine the spectrum displacements corresponding to the natural frequencies of each mode and the appropriate damping ratio from a typical tripartite logarithmic plot of the design spectrum for the building (Figure 7d). The spectrum displacement for each mode is then multiplied by the corresponding participation factor and the mode shape to determine the maximum modal displacements for each mode of the building (Figure 7e). The next step is to combine the maximum modal responses to obtain the expected maximum response of the building. The most commonly accepted method is to use the square root of the sum of the squares method to obtain an estimate of the total displacement of the building (Figure 7e). (However, in cases where the natural frequencies are closely spaced, the sum of the absolute values of the maximum displacements in each of the modes provides a more realistic approximation of the maximum displacement of the building.) It is important to note that the superposition of responses, either by the square root of the sum of squares or by the direct summation of peak values, cannot be used in determining test criteria for equipment. For this purpose, the modal responses must be preserved as a function of frequency.

The general principles of the time history modal analysis method can be illustrated using the same idealized building and analytical model (Figure 8a). The natural frequencies and corresponding mode shapes and participation factors are the same (Figure 8b). Up to this point, the analyses are identical but the calculation of the response of the building will differ. The time history response of each mode is calculated for the earthquake input motions; this calculation yields

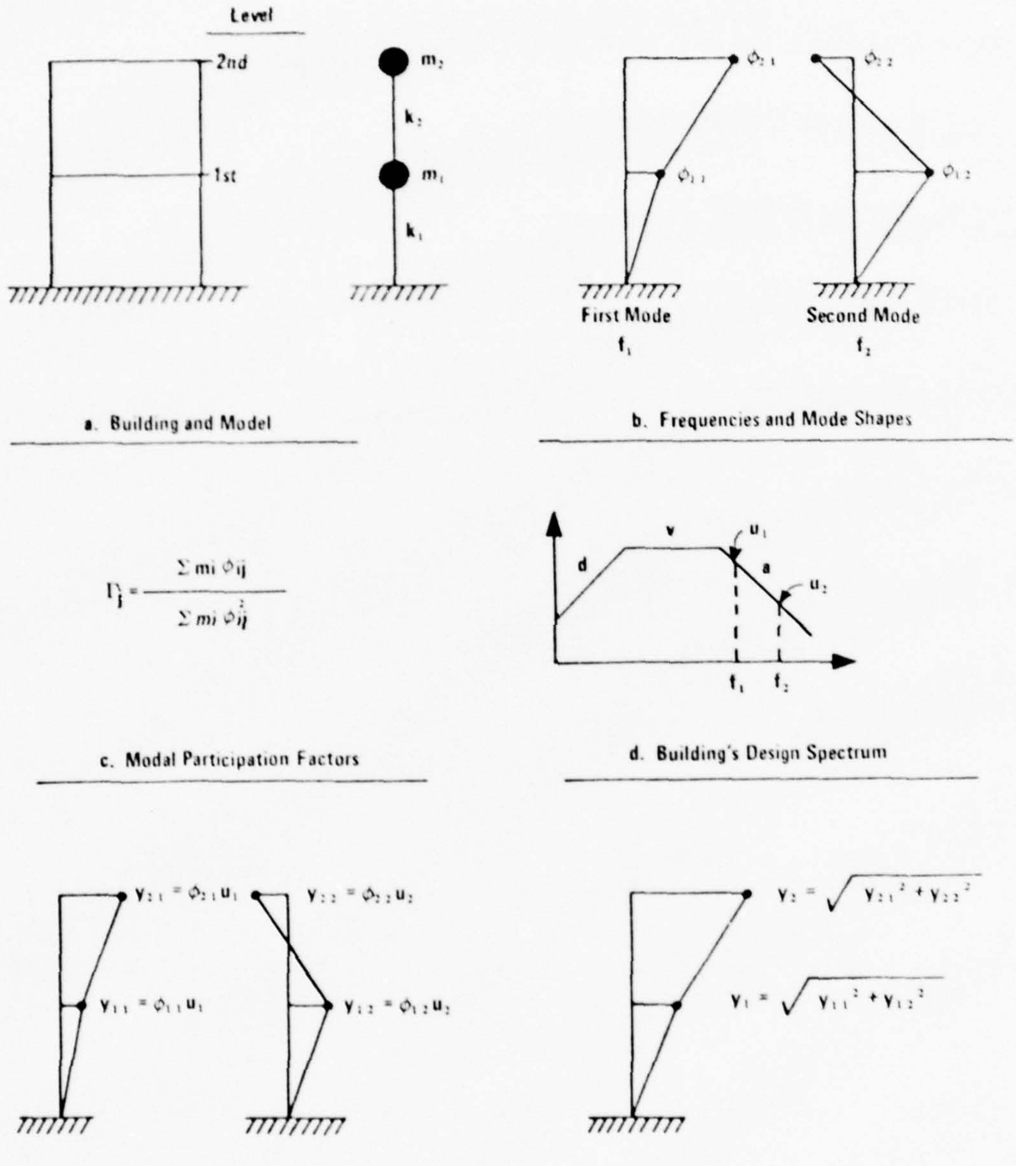


Figure 7. Response spectrum method of dynamic analysis.

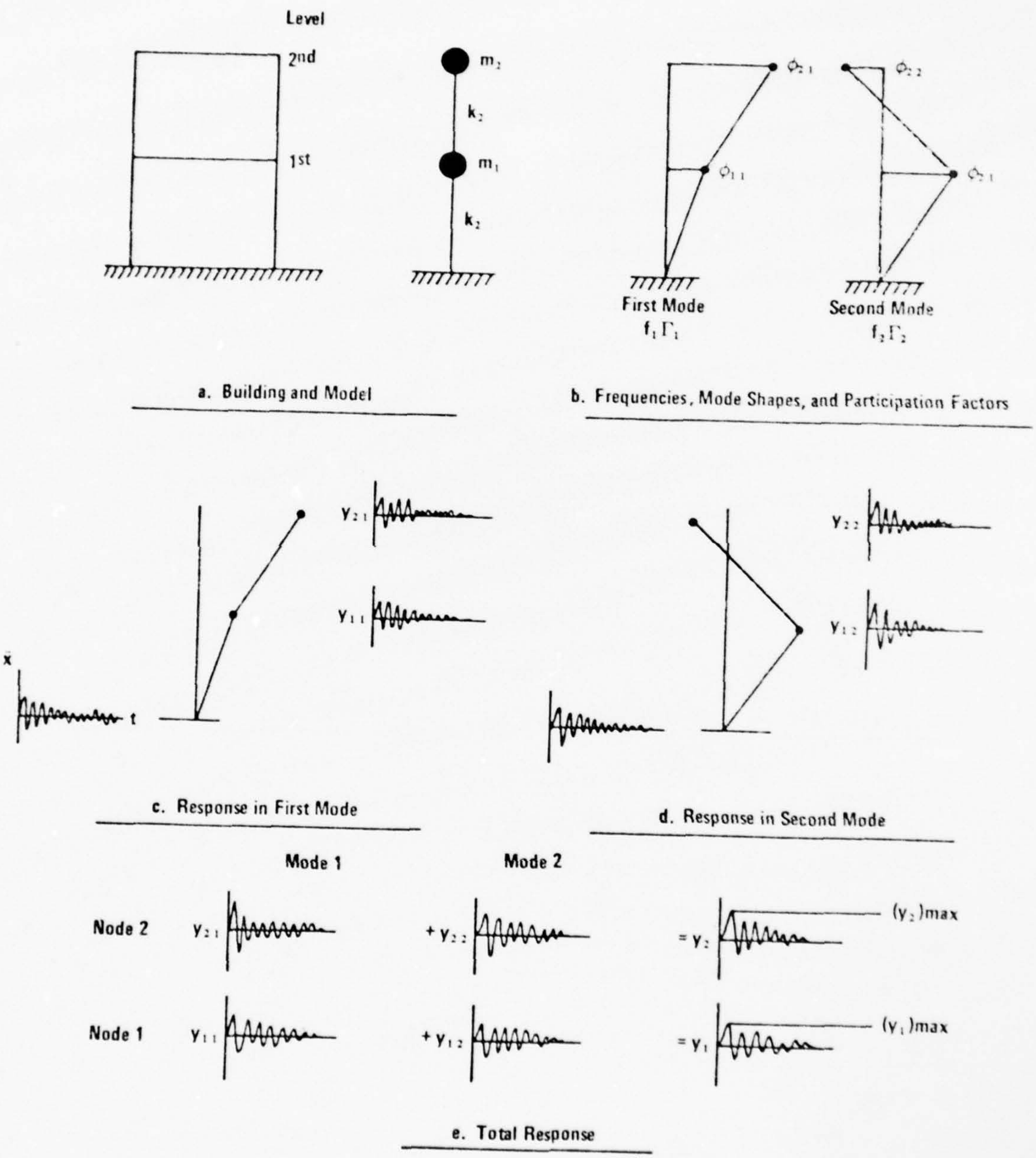


Figure 8. Time history method of dynamic analysis.

time histories for the response at each of the modes (Figures 8c and d). The next step is to combine the time histories of these modal responses. For example, the time history of displacement response of the roof (Mode 2) in the first and second modes are summed point for point in time to produce the time history of the total response of the roof (Figure 8e).

These dynamic analysis methods can be extended to incorporate equipment supported by the floors or other structural members of the building. Both the building structure and the equipment rest on base supports and motions are applied to these supports. Likewise, the equipment responds to the floor motion in the same manner that the building responds to the earthquake motion. Theoretically, a dynamic model of both the building and the equipment could be developed and an analysis conducted to determine the response of the equipment. Realistically, this is impractical because of the large number of degrees of freedom required for the dynamic model and the possibility of ill conditioning the resulting stiffness matrix. Furthermore, most equipment will have negligible interaction effects on the response of the building, as is the case with equipment having relatively little mass and high natural frequencies. Only the mass of such equipment need be included in the mass distribution of the dynamic model of the building. The equipment is then dynamically "uncoupled" from the building and a separate analysis of the equipment can be performed to evaluate the effects of earthquake motions using the output from the building analysis.

In certain situations, the presence of equipment can have a marked effect on the building's response. The equipment must then be included in the dynamic model of the building or its effects analyzed with a simplified model of the building. In such a case, the equipment and the building are said to be dynamically "coupled." For most buildings this situation occurs infrequently. It occurs most frequently with industrial production facilities having large tanks or heavy equipment at intermediate floor levels.

Separate Analysis of Equipment-Structure Response

Two-Degree-of-Freedom System

The response of equipment which is not analyzed as a part of the building structural model generally has been studied through a two-degree-of-freedom model. Figure 9 shows a simplified two-degree-of-freedom model of an item of equipment (the secondary system) mounted on a building structure (the primary system) which is connected to a moving foundation. The absolute displacement (with respect to an inertial frame of reference) of the structure is x_1 and that of the equipment is x_2. For the structure and equipment, respectively, the elastic restoring (spring) rates are k_1 and k_2, the damping values are c_1 and c_2, and the masses are m_1 and m_2. The ground displacement is u.

Equations of Motion. The linearized equations of motion for this model in terms of the absolute displacements x_1 and x_2 are[10]

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 - c_1(\dot{x}_2-\dot{x}_1) - k_2(x_2-x_1) = c_1\dot{u} + k_1u$$

$$m_2\ddot{x}_2 + c_2(\dot{x}_2-\dot{x}_1) + k_2(x_2-x_1) = 0 \qquad \text{[Eq 1]}$$

where dots over a variable indicate differentiation with respect to time. In these equations, the primary variable of interest is $\ddot{x}_2$, which represents the absolute acceleration of the mass of the secondary system. For electrical components such as relays, switches, and circuit breakers, malfunctions (such as chatter or trip-outs) may be caused solely by the absolute acceleration level experienced by the equipment.

Alternately, these equations can be expressed in terms of the relative displacements y_1 and y_2 using the relationship

[10] S. H. Crandall and W. D. Mark, Random Variation in Mechanical Systems (Academic Press, 1963).

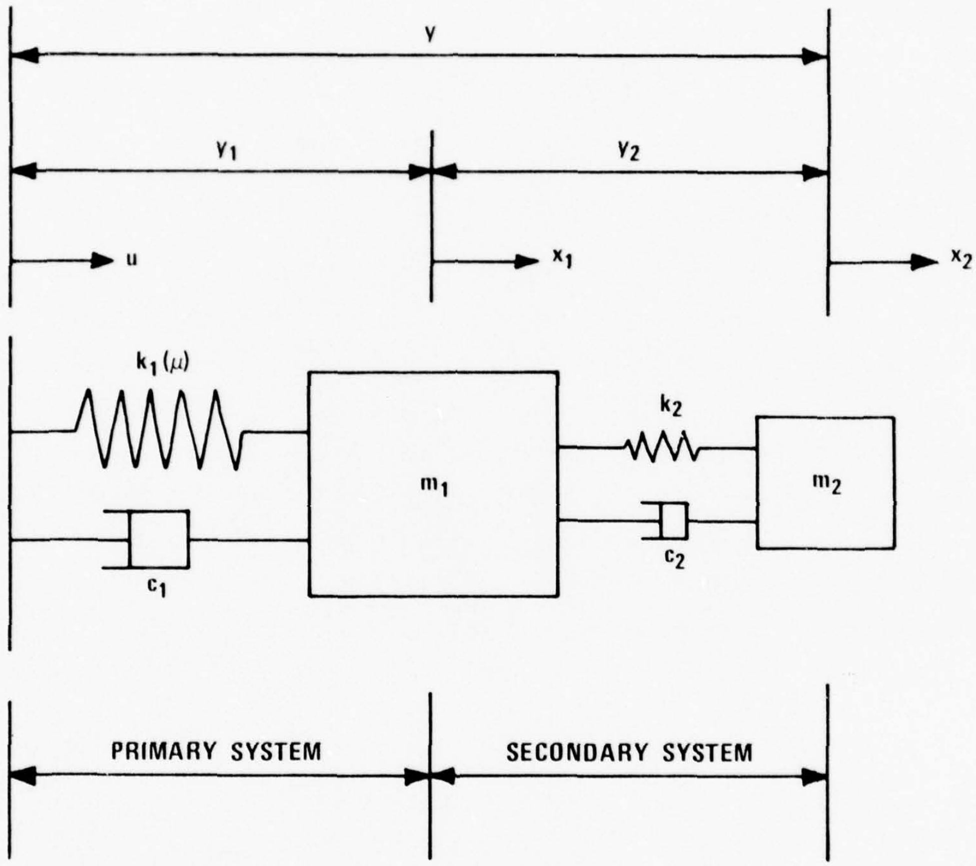


Figure 9. Two-degree-of-freedom model.

$$y_1 = x_1 - u$$

$$y_2 = x_2 - x_1 \qquad \text{[Eq 2]}$$

Upon substitution and rearranging, the equations of motion may be written as

$$m_1\ddot{y}_1 + c_1\dot{y}_1 + k_1y_1 - c_2\dot{y}_2 - k_2y_2 = -m_1\ddot{u}$$

$$m_2(\ddot{y}_1+\ddot{y}_2) + c_2\dot{y}_2 + k_2y_2 = -m_2\ddot{u} \qquad \text{[Eq 3]}$$

In these equations, the primary variable of interest is y_2, which represents the distortion of the spring for the secondary system; y_2 can be related to the maximum allowable force or displacement in the equipment supports. Likewise, the ratio of y_2/y_1 is of interest, since it represents the amplification factor, K, between the spring distortions in the secondary system and the spring distortions in the primary system.

While absolute acceleration is important for comparison to equipment fragility criteria, the literature shows that most investigators[11] have analyzed only the relative motion response (i.e., Eq 3), which is significant for analyzing equipment structural and mounting integrity.

[11] N. M. Newmark, "Earthquake Response Analysis of Reactor Structures," Nuclear Engineering and Design, Volume 20 (1972), pp 303-322; K. K. Kapur and L. C. Shao, "Generation of Seismic Floor Response Spectra for Equipment Design," Specialty Conference on Structural Design for Nuclear Plant Facilities, Volume 1 (17-18 December 1973), pp 29-71; J. M. Biggs and J. M. Roesset, "Seismic Analysis of Equipment Mounted on a Massive Structure," Seismic Design for Nuclear Power Plants, R. J. Hansen, ed. (Massachusetts Institute of Technology [MIT] Press, 1970), pp 319-343; R. N. Clough and J. Penzien, Dynamics of Structures (McGraw-Hill Book Co., Inc., 1975); D. F. Arthur, R. C. Murray, and F. J. Tokarz, "Generation of Floor Response Spectra for Mixed-Oxide Fuel Fabrication Plants," Structural Design of Nuclear Plant Facilities, Volume 1-A (8-10 December 1975), pp 94-108; N. M. Newmark and W. J. Hall, "Earthquake Resistant Design of Nuclear Power Plants," United Nations Educational, Scientific, and Cultural Oranization (UNESCO) Intergovernmental Conference on Assessment and Mitigation of Earthquake Risk (February 1976).

For typical earthquake motions and building response properties, it has been shown[17] that the spectrum for $\ddot{x}_1$ can be closely approximated by the pseudo-acceleration response spectrum, $\ddot{y}_{s1}$, of the primary mass. The appropriate relation is

$$\ddot{x}_1 = \ddot{y}_{s1} = \omega^2 y_1 \qquad \text{[Eq 4]}$$

Thus, the pseudo-acceleration portion of a conventional building response spectrum approximates the absolute floor acceleration spectrum. (Note that this is not the floor response spectrum, estimation of which is discussed later.) Therefore, if the response spectrum method is used for the building analysis, obtaining response spectra for both $\ddot{x}_1$ and y_1 is not worthwhile. The spectrum for y_1 is adequate for establishing both structural and functional equipment test criteria. However, if the time history method is used, direct calculation of $\ddot{x}_1$ is preferred.

Undamped Natural Frequencies. For the undamped case, the equations for determining the natural frequencies of the two-degree-of-freedom system become

$$\begin{aligned} \ddot{y}_1 + \omega_1^2 y_1 - \omega_2^2 \gamma y_2 &= 0 \\ \ddot{y}_1 + \ddot{y}_2 + \omega_2^2 y_2 &= 0 \end{aligned} \qquad \text{[Eq 5]}$$

where the following substitutions have been made:

$\omega_1 = \sqrt{k_1/m_1}$, the uncoupled natural frequency of the primary system

$\omega_2 = \sqrt{k_2/m_2}$, the uncoupled natural frequency of the secondary system

$\gamma = m_2/m_1$, the mass ratio

[17] N. M. Newmark et al., "Response Spectra of Single-Degree-of-Freedom Elastic and Inelastic Systems," Design Procedures for Shock Isolation Systems of Underground Protective Structures, Volume III, TDR-63-3096 (Research and Technology Division, Air Force Weapons Laboratory, June 1964).

For a periodic solution of these equations corresponding to a steady-state vibration with no external force or base motion, consider motion with frequency p and designate the relative displacement y_1 and y_2 in terms of spring distortions S and s, i.e.,[13]

$$y_1 = S \sin(pt)$$
$$y_2 = s \sin(pt) \qquad \text{[Eq 6]}$$

Upon substitution of Eq 6 and their appropriate derivatives into Eq 5, the following matrix equation for the vibration of the system is obtained:

$$\begin{bmatrix} \omega_1^2 - p^2 & -\omega_2^2\gamma \\ -p^2 & \omega_2^2 - p^2 \end{bmatrix} \cdot \begin{Bmatrix} S \\ s \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \qquad \text{[Eq 7]}$$

In order for vibration to occur, the determinant of the matrix in Eq 7 must be zero. Forming this determinant leads to the following frequency equation:

$$p^4 - [(1+\gamma)\omega_2^2 + \omega_1^2] + \omega_1^2\omega_2^2 = 0 \qquad \text{[Eq 8]}$$

With the use of the following relationship, in which $\Lambda = \omega_2/\omega_1$,

$$\alpha = \frac{(1+\gamma)\Lambda^2 + 1}{2\Lambda} = \frac{1}{2}(\Lambda + \frac{1}{\Lambda}) + \frac{\gamma\Lambda}{2} \qquad \text{[Eq 9]}$$

Eq 7 can be transformed into the following form:

$$p^4 - 2\omega_1^2\omega_2^2\alpha p^2 + \omega_1^2\omega_2^2 = 0 \qquad \text{[Eq 10]}$$

[13] N. M. Newmark, "Earthquake Response Analysis of Reactor Structures," Nuclear Engineering and Design, Volume 20 (1972), pp 303-322.

The solution of this equation yields

$$p^2_{1,2} = \omega_1^2\omega_2^2[\alpha \pm \sqrt{\alpha^2-1}\,] \qquad \text{[Eq 11]}$$

For the specialized case when the uncoupled natural frequencies of the primary and secondary systems are identical (i.e., $\omega_1 = \omega_2$), the true natural frequencies of the coupled system are shifted away from the uncoupled natural frequencies by the quantity $\sqrt{\alpha \pm \sqrt{\alpha^2-1}}$.[14] Figure 10 shows this relationship graphically as a function of the ratio p/ω and the mass ratio γ. For example, if the mass of the secondary system is one-tenth the mass of the primary system, the coupled natural frequencies of the system are 1.17 and 0.85 times the uncoupled natural frequency.

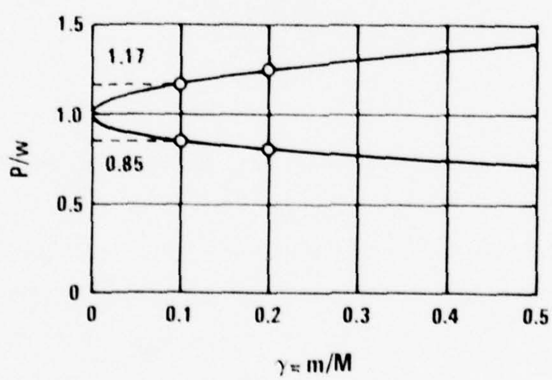


Figure 10. True natural frequencies of the undamped system of Figure 9 as a function of γ, the min ratio. Reprinted by permission of McGraw-Hill Book Co., Inc., from J. P. Den Hartog, Mechanical Vibrations (1956).

[14] J. P. Den Hartog, Mechanical Vibrations (McGraw-Hill Book Co., Inc., 1956).

Mode Shapes. Upon substitution of the values for p from Eq 11 for either the first or second mode, the equations for the mode shapes can be determined as

$$\phi_{11} = 1$$

$$\phi_{12} = \frac{\Delta[\alpha^2+\sqrt{\alpha^2-1}]}{\Delta[\alpha^2+\sqrt{\alpha^2-1}]-1} \qquad \text{[Eq 12]}$$

and

$$\phi_{21} = 1$$

$$\phi_{22} = \frac{\Delta[\alpha^2-\sqrt{\alpha^2-1}]}{\Delta[\alpha^2-\sqrt{\alpha^2-1}]-1} \qquad \text{[Eq 13]}$$

Participation Factor. The participation factor for each of the modes can be determined using the relationship

$$\Gamma_j = \frac{\sum m_i \phi_{ij}}{\sum m_i \phi_{ij}^2} \qquad \text{[Eq 14]}$$

Normalized Spring Distortions. Taking into account that the mode shapes can be normalized to yield a participation factor of unity and various relationships among the various parameters, the following relationships for normalized relative displacements or the normalized spring displacements for each mode can be determined:[15]

$$s_1 = -s_2 = \frac{1}{2\Delta\sqrt{\alpha^2-1}}$$

$$\left.\begin{matrix} S_1 \\ S_2 \end{matrix}\right\} = \frac{1}{2}\left[1 \pm \frac{(1+\gamma)\Delta^2-1}{2\Delta\sqrt{\alpha^2-1}}\right] \qquad \text{[Eq 15]}$$

[15] N. M. Newmark, et al., "Response of Two-Degree-of-Freedom Elastic and Inelastic Systems," Design Procedures for Shock Isolation Systems of Underground Protective Structures, Volume IV, TDR-63-3096 (Research and Technology Division, Air Force Weapons Laboratory, December 1965).

where the plus is to be used with S_1 and the minus with S_2.

For the specialized cases when $\omega_1 = \omega_2$ and the input motions are defined in terms of a response spectrum, the maximum response of the secondary system can be estimated. Using the normalized values of spring distortions, the modal response of the system can be obtained by multiplying the values from Eq 15 by the spectral values of displacement for the particular frequency under consideration and taking the sum of the absolute values of each modal response. Newmark[16] performed these calculations for three cases: a constant spectral displacement bound, a constant spectral velocity bound, and a constant acceleration bound. Moreover, the maximum values of s and S were derived as a function of the mass ratio, γ. For all three cases, it was noted that when the frequency of the secondary system is tuned to the frequency of the primary system and the value of γ is small, the maximum response of the secondary system approaches $1/\sqrt{\gamma}$ times the spectral response value.

Existing Solutions. Since, in general, little is known about the vibrational characteristics of the equipment, except perhaps its approximate weight, an upper bound approach to the response of equipment is to assume that the equipment has a natural frequency equal to the frequency of the supporting structure, i.e., $\omega_1 = \omega_2$, and to calculate the response of the equipment under this condition. Kapur, Biggs, Newmark, and Crandall have developed solutions for the model shown in Figure 9 for the elastic case.[17] The primary differences in the results obtained by each of these authors appear to have been caused by the nature of the assumed excitation. Kapur assumed that the excitation at the ground, $\ddot{U}(t)$, was sinusoidal. Biggs hypothesized that a steady-state response

[16] N. M. Newmark, "Earthquake Response Analysis of Reactor Structures," Nuclear Engineering and Design, Volume 20 (1972), pp 303-322.

[17] K. K. Kapur and L. C. Shao, "Generation of Seismic Floor Response Spectra for Equipment Design," Specialty Conference on Structural Design for Nuclear Plant Facilities, Volume I (17-18 December 1973), pp 29-71; J. M. Biggs and J. M. Roesset, "Seismic Analysis of Equipment Mounted on a Massive Structure," Seismic Design for Nuclear Power Plants, R. J. Hansen, ed. (MIT Press, 1970), pp 319-343; Newmark; S. H. Crandall and W. D. Mark, Random Variation in Mechanical Systems (Academic Press, 1963).

condition of the equipment was too severe based on the irregularities of the ground motion and the damping of the structure. Therefore, he used the actual El Centro ground motion as a forcing function. Newmark used a simple step in velocity, and thereby obtained the acceleration impulse response, from which he derived amplification factors for the secondary equipment. This method therefore does not account for the possibility of resonance build-up between the structure and equipment and may yield lower amplification in some cases. These three authors obtained amplification factors only for relative motion of the secondary system, y_2. However, Crandall assumed white noise excitation, and developed convenient closed form solutions for the four variables, y_1, y_2, $\ddot{x}_1$, and $\ddot{x}_2$. Thus, Crandall's method can be used to address functional (as well as structural) fragility for both the primary and secondary systems. Also, since white noise is closely related to actual earthquake motions,[18] Crandall's method may be expected to yield results about the same as Biggs' method.

A simple comparison was made for all four of these methods, in parallel with a recently published, more rigorous comparison of Kapur's and Biggs' methods.[19] The following parameters were assumed for the model of Figure 9:

$$m_1 = 1625 \text{ kips } (7228 \text{ kN})$$
$$\omega_1 = 12.54 \text{ rad/sec} \qquad \text{[Eq 16]}$$
$$\beta_1 = 0.04$$

$$m_2 = 10 \text{ kips } (44 \text{ kN})$$
$$\omega_2 = 12.54 \text{ rad/sec} = \omega_1 \qquad \text{[Eq 17]}$$
$$\beta_2 = 0.005$$

[18] R. N. Clough and J. Penzien, Dynamics of Structures (McGraw-Hill Book Co., Inc., 1975).
[19] D. F. Arthur, R. C. Murray, and F. J. Tokarz, "Generation of Floor Response Spectra for Mixed-Oxide Fuel Fabrication Plants," Structural Design of Nuclear Plant Facilities, Volume 1-A (8-10 December 1975), pp 94-108.

where the β's are the respective critical damping ratios. These parameters represent realistic values of actual building and equipment properties.[20] The comparison was made by calculating the amplification factor, K, as the ratio of the secondary system response to the primary system response.

For both Kapur's and Biggs' methods, special parametric curves (based on damping ratios) in the respective reports had to be used to calculate the values of K. For Crandall's method, a first approximation of the amplification factor is given by

$$K = \frac{1}{\left(1 + \frac{\beta_2}{2\beta_1} + \ldots\right)\sqrt{\gamma}} \qquad \text{[Eq 18]}$$

where the dots in the denominator indicate higher order terms. For Newmark's method the relation is

$$K = \frac{1}{2\beta_2 + \sqrt{\gamma}} \qquad \text{[Eq 19]}$$

the amplification factors obtained for the problem described by Eqs 16 and 17 are:

$$\begin{aligned} &\text{Kapur:} && K = 23.0 \\ &\text{Biggs:} && K = 10.5 \\ &\text{Crandall:} && K = 11.3 \\ &\text{Newmark:} && K = 11.3 \end{aligned} \qquad \text{[Eq 20]}$$

Comments in the literature[21] indicate that Kapur's method is probably too conservative. Hence, this method is not recommended herein for further consideration. Biggs', Crandall's, and Newmark's methods

[20] J. D. Prendergast and W. E. Fisher, Seismic Structural Design/Analysis Guidelines for Buildings, Special Report M-206/ADA037747 (CERL, 1977).

[21] N. M. Newmark and W. J. Hall, "Earthquake Resistant Design of Nuclear Power Plants," UNESCO Intergovernmental Conference on Assessment and Mitigation of Earthquake Risk (February 1976).

gave nearly equivalent results in this example, but this consistency may not be true in general. Of the three, Newmark's method is the simplest to apply.

Multi-Degree-of-Freedom-System

The previous section presented a simple two-degree-of-freedom idealization of the equipment-structure interaction problem. Recent studies by Newmark and Hall[22] have considered more complex primary systems with a simple secondary system (such as that shown in Figure 11). The primary system need not be a linear spring mass arrangement; however, the secondary system must be a simple spring mass system. These studies have indicated that, in general, the maximum response of a light equipment mass attached to a structure will not exceed the basic response spectrum for the building multiplied by an amplification factor, K, defined as follows

$$K = \frac{1}{\beta_e + \beta_s + \sqrt{\gamma}} \qquad \text{[Eq 21]}$$

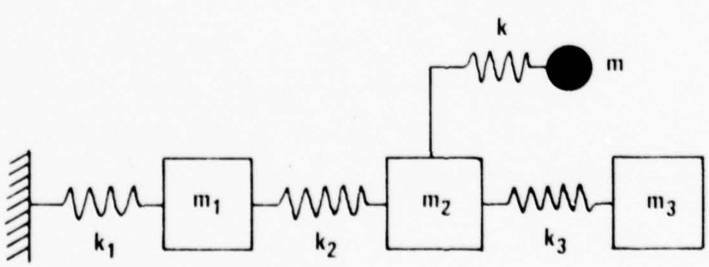


Figure 11. Light secondary system added to primary system.

[22] N. M. Newmark and W. J. Hall, "Earthquake Resistant Design of Nuclear Power Plants," UNESCO Intergovernmental Conference on Assessment and Mitigation of Earthquake Risk (February 1976).

where β_e = critical damping ratio for the equipment

β_s = critical damping ratio for the structure

γ = ratio of the generalized mass of the equipment to the generalized mass of the structure when the mode shape is taken so as to have a unit participation factor.

When Eq 21 is applied to the problem defined by Eqs 16 and 17, a value of K = 8.1 is obtained. This is somewhat less than the previous values shown in Eq 20. It is recommended that the amplification factor given by Eq 21 be used with the building response spectrum to construct equipment response spectra in accordance with the procedures outlined in the next two sections for the following reasons:

1. In many instances, a purely linear elastic analysis may be unreasonably conservative when one considers that, even up to the near yield point range, there are nonlinearities of sufficient amount to reduce required design levels considerably.

2. The computational simplicity of the expressions makes it easy to implement. The results of a routine modal analysis of the building will yield the frequencies, mode shapes, and discrete masses from which the generalized masses can be calculated. Thus, all that is required are estimates of the mass of the equipment and the equipment's damping value. No elaborate computation procedures are required beyond these estimates.

3. The expression includes the major parameters which govern the response of the secondary system, i.e., the critical damping ratios for the structure and the equipment and the ratio of the generalized mass of the equipment and the structure.

4. Through the mode shapes, the amplification factors may be modified to yield upper bound estimates of the response of equipment at various floor levels in the building as well as the roof.

5. The fact that the primary system experiences inelastic deformations does not limit or prevent the use of this expression. This is

particularly significant because most buildings, including critical buildings (such as hospitals), are designed to undergo minor inelastic deformations during severe earthquakes.

Equipment Test Criteria--Response Spectrum Method

Equipment Response Spectrum Construction

For most buildings, a dynamic analysis is performed using the response spectrum modal analysis method. The information from the response spectrum modal analysis, along with the equipment's location, estimated weight, and damping ratio, yields sufficient data for constructing an approximate equipment response spectrum suitable for use as waveform test criteria. The equipment response spectrum should be constructed in accordance with the following steps:

Step 1. Obtain the design spectrum used in the dynamic analyses of the building which incorporates the appropriate critical damping ratio and ductility factor for the building.

Step 2. Obtain the values for the mass lumped at each level of the building and the natural frequencies, mode shapes, and modal participation factors determined from the dynamic analysis of the building. If the modal participation factors are not equal to unity, multiply each mode shape by its respective participation factor to obtain normalized mode shapes with participation factors equal to unity.

Step 3. Compute the generalized mass in each of the modes using the formula

$$\overline{M}_j = \sum m_i \overline{\phi}_{ij}^2 \qquad \text{[Eq 22]}$$

where $\overline{M}_j$ = generalized mass in the j^{th} mode

m_i = mass lumped at the i^{th} level of the building

$\overline{\phi}_{ij}$ = normalized mode shape component for the j^{th} mode.

Step 4. Compute the resonant amplification factors for each of the modes by the equation

$$K_j = \frac{1}{\beta_e + \beta_s + \sqrt{\gamma_j}} \qquad \text{[Eq 23]}$$

where K_j = amplification factor for the j^{th} mode

β_e = damping ratio for the equipment

β_s = damping ratio for the building

γ_j = ratio of the generalized mass of the equipment to generalized mass of the j^{th} mode of the building.

Step 5. Determine the building's design spectrum acceleration level, a_j, for each of the building's natural frequencies, by reading it directly from the building's design spectrum.

Step 6. Compute the ordinates of the equipment response spectrum at each of the building's natural frequencies from the relationship

$$z_{ij} = K_j \left| \frac{\phi_{ij}}{\phi_{Nj}} \right| a_j \qquad \text{[Eq 24]}$$

where z_{ij} = equipment response spectrum ordinate for the i^{th} floor level of the j^{th} mode

ϕ_{ij} = normalized mode shape ordinate for the i^{th} level of the j^{th} mode

ϕ_{Nj} = normalized mode shape ordinate for the N^{th} level of the j^{th} mode (N is the uppermost level)

i = level of the building on which equipment is located

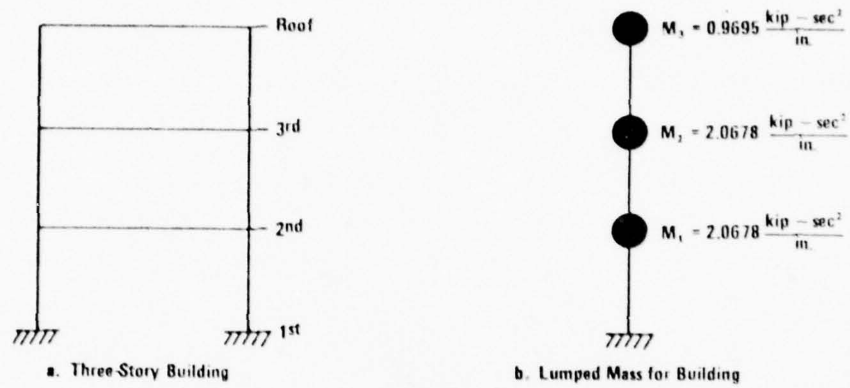
N = uppermost level of the building.

Step 7. Construct the equipment response spectrum by plotting the ordinates for each of the building's modes and connecting these points by straight lines. Alternately, the frequency band for each ordinate of the equipment response spectrum may be broadened at each of the building's natural frequencies to account for potential structural frequency variations. For frequencies below one-third the fundamental frequency of the building, the equipment response spectrum is taken to be equal to the building design spectrum constructed for a damping ratio of β_e. For frequencies three times the highest natural frequency of the building considered in the dynamic analysis, the equipment response spectrum is taken to be equal to the building's design spectrum. Construction of the equipment floor response spectrum is completed by connecting the existing portions of the equipment response spectrum with straight lines in the regions near the fundamental and highest natural frequencies of the building.

Example

The following example illustrates the construction of a floor response spectrum using the procedures outlined above. The example considers an item of heavy equipment mounted on the third floor of a three-story building. The equipment is assumed to weigh 10 kips (0.026 kip-sec^2/in.) (44 kN [0.0045 Mkg-sec^2/m]) and to have a damping ratio of $\beta_e = 0.03$. The building is assumed to be a simple steel rigid frame (Figure 12a) also with a damping ratio of $\beta_3 = 0.03$ and an allowable ductility factor of $\mu = 1.5$. The building behavior is assumed to be modeled by a discrete lump mass system; Figure 12b shows the masses concentrated at the roof and floor levels. The natural frequencies, mode shapes, and modal participation factors for the building have been previously computed by modal analysis techniques; the results are presented in Figure 12c.[23] Furthermore, it is assumed that peak ground acceleration for the location of the building is 0.4 g and that the inelastic

[23] W. K. Stockdale, Seismic Design Methods for Military Facilities--Preliminary Recommendations, Interim Report M-184/ADA027384 (CERL, 1976).



a. Three-story building   b. Lumped mass for building

$f_1 = 2.00$ Hz
$f_2 = 5.60$ Hz
$f_3 = 9.93$ Hz

Level	Mode Shape ϕ_{ij} Mode 1	Mode 2	Mode 3
Roof	3.475	-1.578	0.603
3rd	2.372	0.662	-0.836
2nd	1.000	1.000	1.000

$\Gamma_1 = 0.407$
$\Gamma_2 = 0.354$
$\Gamma_3 = 0.239$

c. Natural frequencies, mode shapes and modal participation factors

Level	Normalized Mode Shapes, $\bar{\phi}_{ij}$ Mode 1	Mode 2	Mode 3
Roof	1.414	-0.559	0.144
3rd	0.965	0.234	-0.200
2nd	0.407	0.354	0.239

d. Normalized mode shapes

Level	Mass	$\bar{M}_i$, Generalized Mass Mode 1	Mode 2	Mode 3
Roof	0.9695	1.938	0.303	0.020
3rd	2.0678	1.926	0.113	0.083
2nd	2.0678	0.343	0.259	0.118
	$\sum$	4.207	0.675	0.221

e. Generalized masses

Figure 12. Example problem. SI conversion factor: 1 kip-sec^2/in. = 0.0176 Mkg-sec^2/m.

response spectrum for the building was constructed in accordance with the procedures in CERL Special Report M-209 to yield the design spectrum shown in Figure 13.

The floor response spectrum is constructed as follows:

Step 1. The building's design spectrum was constructed for an effective peak ground acceleration of 0.4 g, a damping ratio of 0.03, and a ductility factor of 1.5. The acceleration, velocity, and displacement bounds of the building's design spectrum below 8 Hz are

$$\begin{aligned} a &= 0.82 \text{ g} \\ v &= 30.72 \text{ in./sec } (78.03 \text{ cm/sec}) \\ d &= 20.16 \text{ in.} \end{aligned} \qquad \text{[Eq 25]}$$

Above 33 Hz the acceleration bound of the building's design spectrum equals the effective peak ground acceleration, i.e., 0.4 g. There is a linear transition in acceleration between 8 and 33 Hz.

Step 2. The masses concentrated at the roof and floor levels are shown in Figure 12b and the natural frequencies, mode shapes, and modal participation factors for the building are presented in Figure 12c. Since the modal participation factors are not equal to unity, each mode shape must be multiplied by its respective participation factor to produce a normalized mode shape. The normalized mode shapes are presented in Figure 12d. For example, the calculations associated with computing the normalized mode shape for the first mode are illustrated below:

$$\begin{aligned} \bar{\phi}_{ij} &= \Gamma_j \phi_{ij} \\ \bar{\phi}_{31} &= 0.407\ (3.475) = 1.414 \\ \bar{\phi}_{21} &= 0.407\ (2.372) = 0.965 \\ \bar{\phi}_{11} &= 0.407\ (1.000) = 0.407 \end{aligned} \qquad \text{[Eq 26]}$$

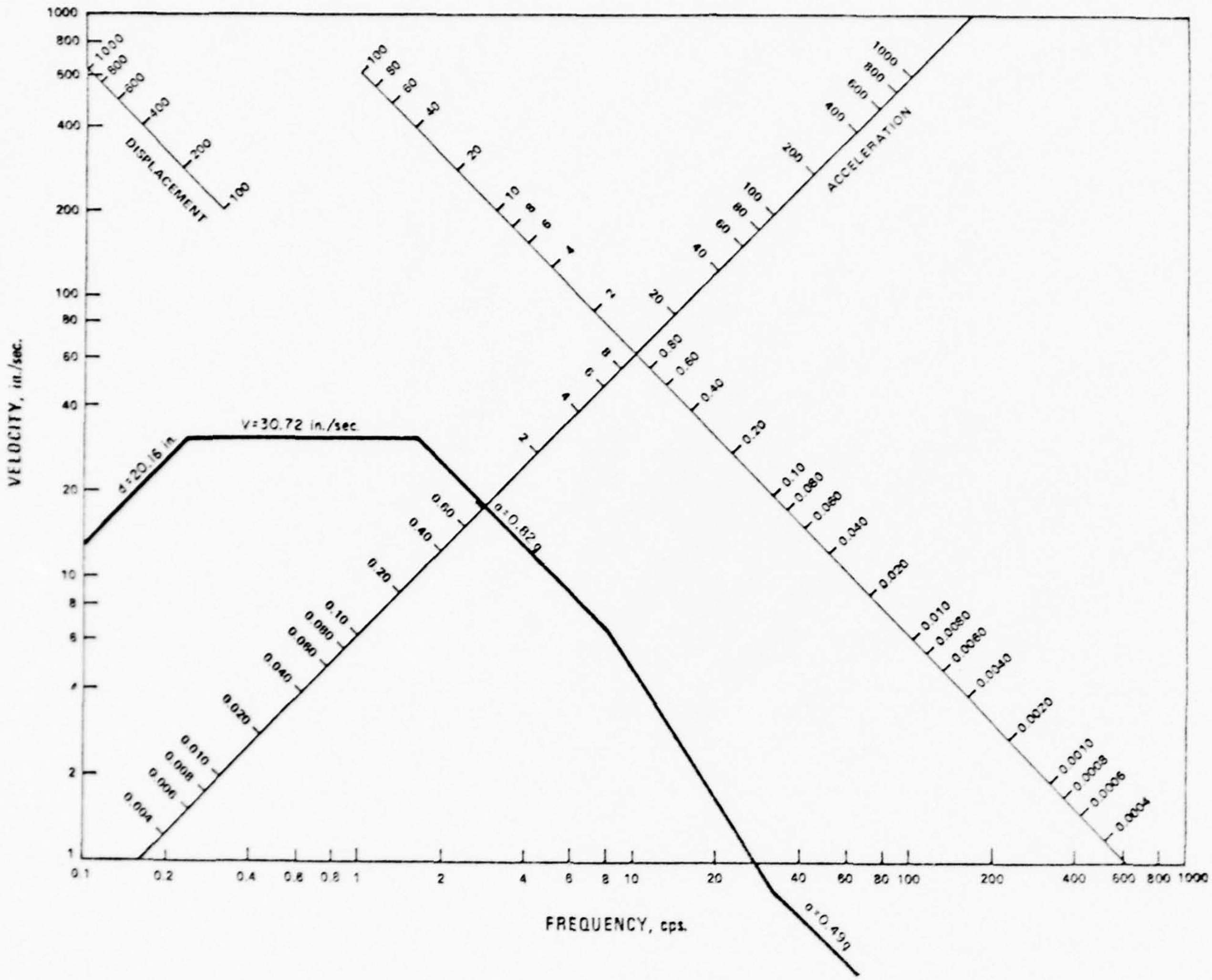


Figure 13. Building design spectrum, 3 percent damping and ductility factor equal to 1.5. SI conversion factor: 1 in. = 25.4 mm.

Step 3. The generalized mass in each of the modes is computed using the masses concentrated at each level of the building and the normalized mode shapes from Step 2. These calculations are summarized in Figure 12e and yield

$$\begin{aligned} \overline{M}_1 &= 4.207 \text{ kip-sec}^2/\text{in. } (0.740 \text{ Mkg-sec}^2/\text{m}) \\ \overline{M}_2 &= 0.675 \text{ kip-sec}^2/\text{in. } (0.012 \text{ Mkg-sec}^2/\text{m}) \\ \overline{M}_3 &= 0.221 \text{ kip-sec}^2/\text{in. } (0.004 \text{ Mkg-sec}^2/\text{m}) \end{aligned} \qquad \text{[Eq 27]}$$

Since the equipment is modeled as a single-degree-of-freedom system, the generalized mass for the equipment is equal to its actual mass, i.e., 0.26 kip-sec^2/in. (0.0045 Mkg-sec^2/m).

Step 4. The resonant amplification factor for each of the modes is calculated by Eq 23 as follows:

$$K_1 = \frac{1}{0.03 + 0.03 + \sqrt{0.026/4.207}} = 7.21$$

$$K_2 = \frac{1}{0.03 + 0.03 + \sqrt{0.026/0.672}} = 3.90$$

$$K_3 = \frac{1}{0.03 + 0.03 + \sqrt{0.026/0.221}} = 2.48$$

Step 5. From Figure 13, the building's design spectrum acceleration levels at each of its natural frequencies are

$$\begin{aligned} a_1 &= 0.82 \text{ g} \\ a_2 &= 0.82 \text{ g} \\ a_3 &= 0.76 \text{ g} \end{aligned} \qquad \text{[Eq 28]}$$

Step 6. Since the equipment is located on the third floor, i.e., the second level, the mode shape ordinates for both the third floor and roof level are required to compute the ordinates of the equipment floor

response spectrum at each of the building's natural frequencies. These values are obtained directly from Figure 12d. Likewise, K_j and a_j were determined in Step 4 and Step 5, respectively. The floor response spectrum ordinates are determined using Eq 24:

$$z_{21} = 7.21 \left| \frac{0.965}{1.414} \right| 0.82 = 4.03 \text{ g}$$

$$z_{22} = 3.90 \left| \frac{0.243}{-0.559} \right| 0.82 = 1.34 \text{ g}$$

$$z_{23} = 2.48 \left| \frac{-0.200}{0.144} \right| 0.76 = 2.62 \text{ g}$$

Step 7. To construct the floor response spectrum, the plotted acceleration ordinates determined in Step 6 were connected with straight lines. At frequencies of below $(1/3)f_1 = 0.67$ Hz and above $3f_3 = 27.79$ Hz, the spectrum is taken to be equal to the building's design spectrum. To complete the construction, the existing portions of the spectrum were connected with straight lines to form the spectrum shown in Figure 14.

Equipment Test Criteria--Time History Method

When a dynamic analysis of the building has been performed by the time-history modal analysis method or direct step-by-step integration of the equations of motions, time histories of the response at the various floor levels will generally be available. This analysis can be applied in either case. To generate equipment test criteria, the time histories of the floor response should be arranged to yield absolute accelerations of the floors. The resulting acceleration time histories may be used to formulate equipment test criteria in either of two ways.[24]

The acceleration time histories may be used to compute floor response spectra, with the test criteria being formulated in terms of

[24] J. S. Bendat and A. G. Piersol, Random Data: Analysis and Measurement Procedures (Wiley-Interscience, 1971).

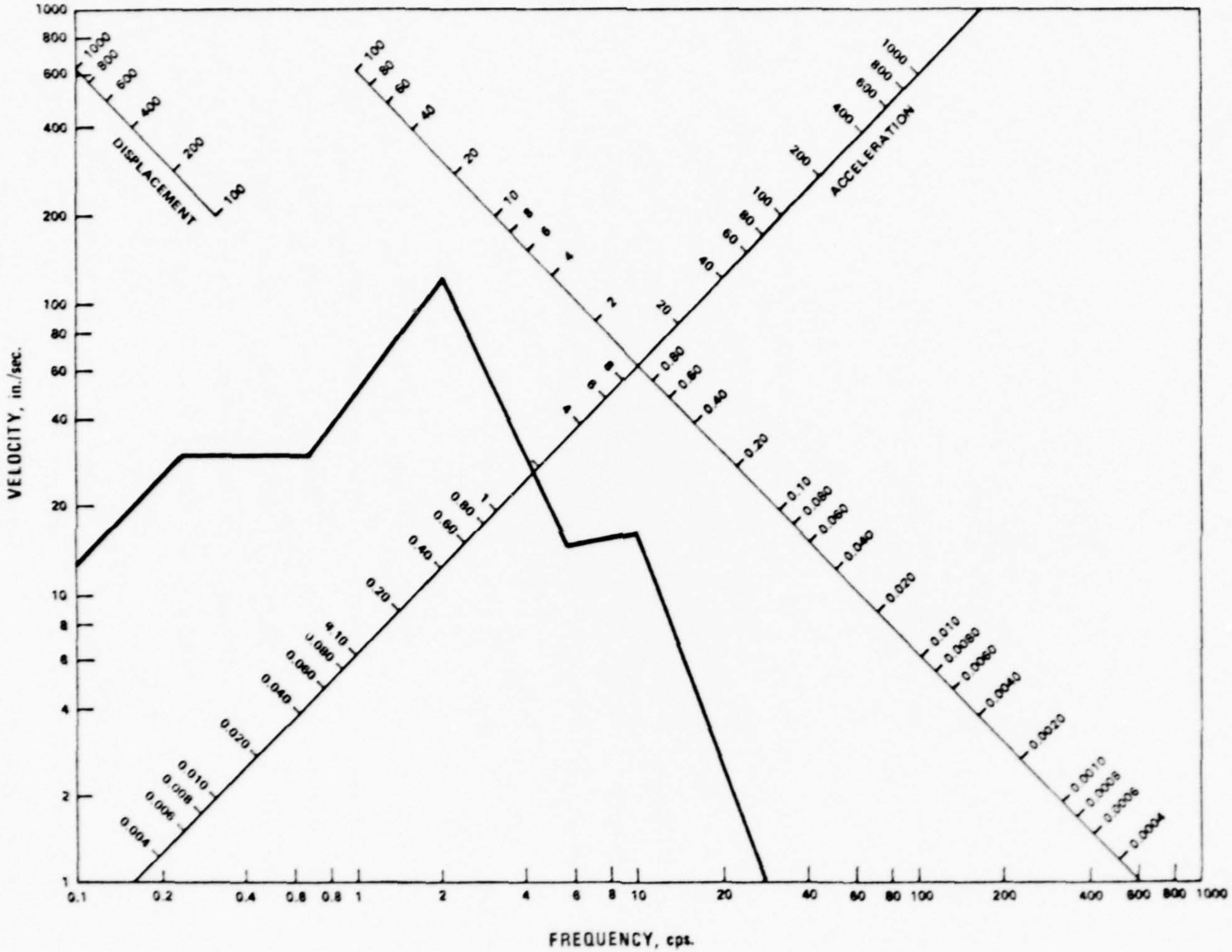


Figure 14. Equipment response spectrum. SI conversion factor: 1 in. = 25.4 mm.

floor response spectra as in the previous section. Alternately, the acceleration time history for a specific floor is sufficient to define test criteria for equipment at this location in the structure. Thus, the acceleration time history may be used directly as the input to a shake table, provided the maximum acceleration, velocity, and displacement values associated with the acceleration time history are within the table's physical capabilities.

In practice, the number of different earthquake time histories used to define the seismic excitation of the building is generally limited to one or two; consequently, the corresponding number of time history response solutions is limited. Since the true earthquake time history for a future earthquake cannot be predicted, the true response cannot be calculated. Furthermore, the uncertainties in estimating structural parameters used in the analysis of the primary structure can cause uncertainties in the response calculations. It is therefore highly desirable to apply appropriate statistical methods, even if only one acceleration trace is available. The statistical methods described below address the case in which only one acceleration trace is available from a time history solution.

The typical acceleration trace under consideration is assumed to be a nonstationary random trace[25] which has a Fourier transform and is nonzero over a finite time interval, T. The nonstationary property means that its statistical properties are not constant with respect to time.

Let $\{a(t)\}$ denote the floor acceleration time history. The use of brackets around the variable denotes that the function is random. This function may be written as the product of two functions, each of which is more amenable to analysis:

$$\{a(t)\} = \psi(t)\ \{\alpha(t)\} \qquad \text{[Eq 29]}$$

[25] J. S. Bendat and A. G. Piersol, Random Data: Analysis and Measurement Procedures (Wiley-Interscience, 1971).

where $\psi(t)$ is deterministic, and $\{\alpha(t)\}$ is a stationary random function having a mean value of zero and a variance of unity.

$\psi(t)$ may be identified as an intensity function[26] which is always positive (i.e., $\psi(t) \geq 0$). This function can be obtained by first squaring $\{a(t)\}$ to obtain $\{a^2(t)\}$, and then short-time averaging (or, equivalently, low-pass filtering) the squared function. Then $\psi(t)$ is an estimate of the time-varying root-mean-square value of $\{a(t)\}$. If many acceleration traces (i.e., an ensemble) of $\{a(t)\}$ were available, $\psi(t)$ could be calculated more accurately by ensemble-averaging. The time averaging is acceptable when only one trace is available.[27]

Figure 15a shows a typical trace of $\{a(t)\}$. Figure 15b shows a possible appearance of $\psi(t)$ obtained from $\{a(t)\}$ by short-time averaging. If $\{a(t)\}$ is divided by $\psi(t)$ point for point in time, the result is $\{\alpha(t)\}$:

$$\{\alpha(t)\} = \frac{\{a(t)\}}{\psi(t)} \qquad \text{[Eq 30]}$$

which will be stationary random with a mean of zero and variance of unity. Figure 15c shows the possible appearance of $\{\alpha(t)\}$.

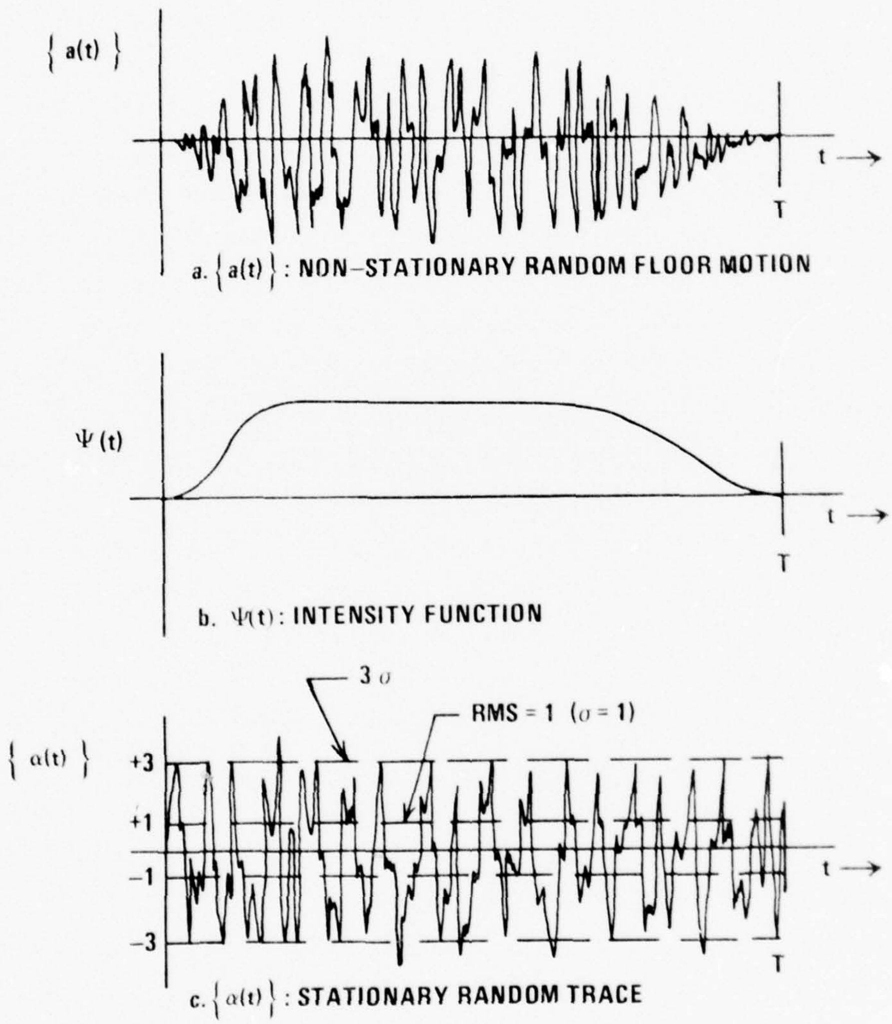
The frequency content of $\{\alpha(t)\}$ will be composed of vibrations at or near the natural frequencies of the building. The conventional method for analyzing the frequency content of stationary random data is through spectral density, which is closely associated with and involves the Fourier transform.[28] Spectral density is basically a statistical method of viewing data as a function of frequency. For an acceleration trace, such as $\{\alpha(t)\}$, the spectral density can be calculated, and its units are in terms of acceleration squared per hertz. Details of the calculation are well documented[29] and will not be given here. The

[26] R. N. Clough and J. Penzien, Dynamics of Structures (McGraw-Hill Book Co., Inc., 1975).

[27] J. S. Bendat and A. G. Piersol, Random Data: Analysis and Measurement Procedures (Wiley Interscience, 1971).

[28] Bendat and Piersol.

[29] Bendat and Piersol.



Typical 15. Typical response trace properties.

stationary spectral density calculated from $\{a(t)\}$ will be denoted as G(f), where f is frequency.

Figure 16a shows a typical plot of how G(f) could appear. The natural frequencies of the building, shown as f_1, f_2, f_3, and f_4, should be positions of peak values of G(f), indicating that these frequencies are dominantly present in the data. The effect of structural ductility would be to blunt the peaks and essentially smear them toward the lower frequencies.

A standard error, σ_ε, can be calculated for a spectral density. This error is a function of both the amount of data available and the desired spectrum resolution band width. The standard error can be quite large if only one data trace, $\{a(t)\}$, is available for spectral analysis. The value of σ_ε can be used to establish upper confidence bands on the calculated spectral density curve, G(f). Figure 16b shows G(f) and two curves above it at the $+1\sigma_\varepsilon$ and $+2\sigma_\varepsilon$ levels; there will be a 50 percent probability that the true spectrum falls below G(f), 84.1 percent probability at the $+1\sigma_\varepsilon$ curve, and a 97.9 percent probability at the $+2\sigma_\varepsilon$ curve.

Any multiple of the standard error can be selected to increase the statistical confidence level in any frequency range of the spectral density curve. A new shaped spectrum can then be used to generate corresponding random floor acceleration traces for use in driving a shake table. The standard error can be reduced if more acceleration traces such as $\{a(t)\}$, are available at the same floor location, as generated from artificial earthquake motions having identical statistical properties. Technology available for the conversion of spectral density functions into time history motions is discussed in the next section.

To summarize, if a time history floor acceleration trace $\{a(t)\}$ is available, it may be used directly as a test criterion to drive a shake table, assuming that the required motions are within the physical limits of the lab facility. In this case, the errors in both intensity and frequency content of $\{a(t)\}$ can be quite large because of uncertainties in ground motion and building structural parameters. Statistical confidence can be increased by spectral density analysis. By selecting a

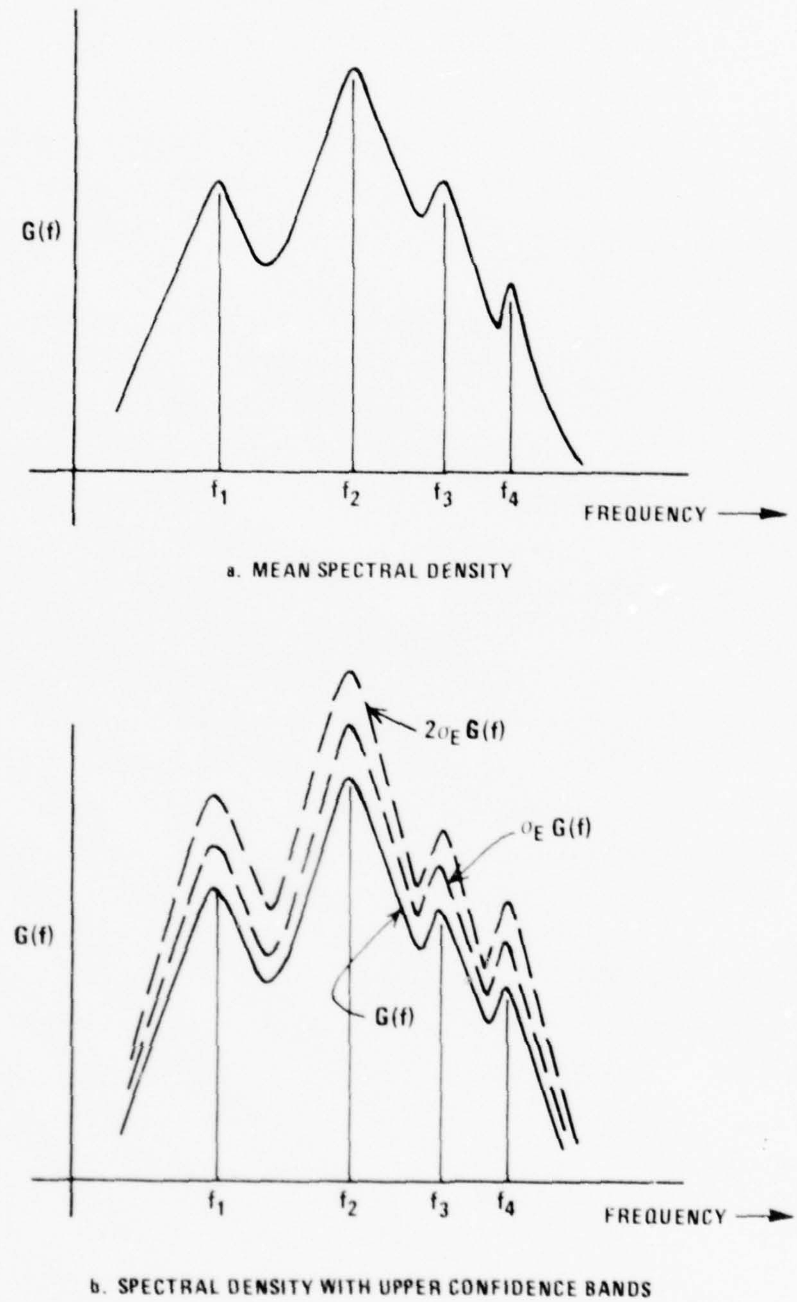


Figure 16. Typical spectral density presentation.

higher confidence level of the spectrum based on either its overall or band limited standard error, a new acceleration trace can be generated and used as the test criterion to drive a shake table.

Development of Test Waveforms

The final phase in specifying test criteria for equipment is the conversion of the frequency domain representation of the data and the amplitude intensity function into acceleration time histories for use in driving a shake table.

The previous sections recommended that the frequency representation from a time-history approach be in the form of spectral density, while that from a response spectrum approach be in the form of a shock spectrum. The amplitude intensity function, $\psi(t)$, is generated in the process of finding the effective stationary spectral density from the time history approach. For the response spectrum approach, the intensity function is not obtained or carried through the derivations, and should be at least roughly estimated before test waveforms are generated. For this purpose, a crude intensity function may be formed from an envelope of the positive peaks of a representative earthquake ground acceleration time history, normalized to a maximum value of unity.

Several computer programs are available for conversion of test criteria into acceleration waveforms.[30] The SIMQKE program appears most appropriate for this work. This program can generally be used in three modes, or options. In all options, the primary output is an acceleration trace, and an intensity function can be prescribed as input data. In option 1, the primary input is a target shock response spectrum for use from a response spectrum approach. In option 2, the spectral density is specified for use from a time history approach. Option 3 allows the user to re-input a previously generated spectral density and to specify desired changes in its shape.

[30] R. P. Schmitz and G. Chan, Evaluation and Illustration of Waveform Synthesis Techniques for Earthquake Design and Analysis Application (Sperry Rand Corp., January 1974); D. Gasparini, SIMQKE: A Program for Artificial Motion Generation, National Science Foundation Grant ATA 74-06935, Internal Study Report No. 3 (Department of Civil Engineering, MIT, January 1975).

Figure 17 demonstrates the capability of the SIMQKE program to generate an acceleration trace to match a target response spectrum. Typically, the computed response spectrum fluctuates about the target values as shown. This phenomenon occurs generally, no matter which of the available programs is used to generate the acceleration waveforms. In the SIMQKE program, an iterative procedure is built in to improve the matching. Perfect matching can never be obtained; hence, the accuracy in matchiaq must be accepted as a trade-off between test requirements and program running time.

The inability to match a prescribed spectrum perfectly is often the subject of controversy between equipment manufacturers and test engineers. If the equipment fails, the manufacturer has the right to claim that the item was overtested. On the other hand, if it survives, the engineer may be seriously concerned that certain frequencies did not have adequate amplitude representation. In cases where such a controversy exists, tests should be repeated using a different acceleration trace each time, providing the equipment can be restored to its original form after each test. Each acceleration trace should be generated to match the same target spectrum. This course of action will yield a partial fragility test of the equipment, from which a crude estimate of the probability of failure can be obtained. It may be necessary to proceed to a full fragility test, or the crude estimate of the probability of failure may be accepted. Alternatively, the manufacturer could redesign the equipment to correct the failure so that it survives the test level.

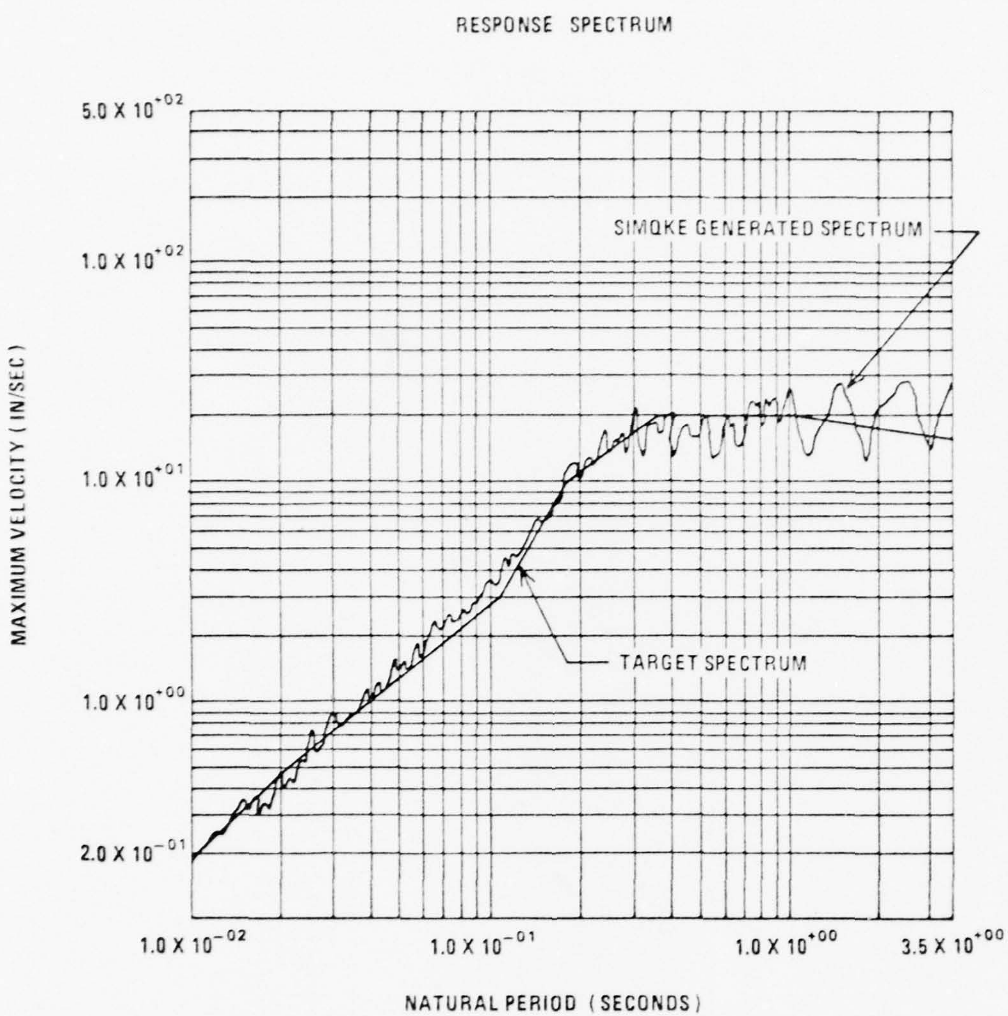


Figure 17. SIMQKE shock spectrum matching. SI conversion factor: 1 in. = 25.4 mm.

5 TEST REPORT REQUIREMENTS

Test results must be reported using the detailed information and report format requirements defined in MIL-STD-831.[31] The supplementary comments provided here do not override or contradict those requirements. When doubt exists, the provisions of the military standard should govern the course of action in reporting test results. IEEE Standard 344-1975[32] also provides relevant information on reporting results.

Supplementary Information

Care must be taken to insure that test data can be interpreted with a minimum of subjectivity. A complete test report should be required. The cost of such a report is expected to be relatively small compared to the costs of equipment, time, and labor. A typical report should include the following:

1. A detailed description of why the unit must be tested and what results are considered important.
2. The authorizing agency, the funding, and the time schedule restrictions.
3. A description of the unit to be tested in terms of where or how it fits into a critical system or subsystem, and what components are to be tested. Critical interfaces with other systems should also be described. (See also the definition of Test File in MIL-STD-831.)
4. A description of the operating conditions under which the unit must be tested, including such information as pressures, temperatures, flow rates, etc.

[31] Preparation of Test Reports, MIL-STD-831 (Headquarters, Defense Supply Agency, Standardization Division, 28 August 1963).
[32] IEEE Recommended Practices for Seismic Qualification of Class IE Equipment for Nuclear Power Generating Stations, IEEE 344-1975 (IEEE, 1975)

5. A definition of what constitutes functional and/or structural failure of the test unit in general and the components of equipment in particular.

6. The loading requirements, which should be specified before testing is authorized. The required 100 percent test level should be recorded as specified, usually in the form of a shock spectrum. Variations of this loading for special conditions should be stated in detail.

7. A description of the testing machine's dynamic capabilities in terms of maximum displacement, velocity, acceleration, frequency range, table weight, test mass weight, or any other pertinent specifications.

8. A description of the instrumentation used; the calibration date should be given, along with a specification that the calibration system be traceable to the National Bureau of Standards.

9. A description of all testing methods and all detailed procedures for conducting the tests. The procedures should be recorded as testing progresses. Each action should be listed on a tabulated form so that events can be read in chronological order; in particular, all anomalies, failures, and corrective actions should be described.

10. A standard tabulation format, which should be used to summarize test results. This format, as described below, should include sufficient information to assess the hardness of the unit without further reference to detailed methods and procedures. This summary tabulation is recommended <u>in addition to</u> the requirement for a tabular summary sheet in MIL-STD-831.

11. An appendix containing all raw test data in tabular form.

Test Summary Format

The purpose of the test summary format is to provide a standard presentation from which enough significant information can be extracted to facilitate assessment of the unit's hardness. Figure 18 illustrates a suitable format and typical entries. The following minimum information should be provided:

UNIT TITLE: Air Compressor Control Panel

DATES: Jan 15-18, 1974

TEST MACHINE: C.O.E. B, Uniaxial

TEST	AXIS	LOADING	FAILURE DESCRIPTION	CLASSIFICATION	
				DELAY	CONSISTENCY
5	X	50%	None		
⋮					
9	Y	50%	Hi-after cooler temp. fault trip	Q	L
⋮					
⋮					
14	Y	100%	Fault on disable vibration switch	F	C

Figure 18. Typical test summary format.

1. Heading information, including a title, description of the unit, the test machine used, and the date or span of dates over which testing was conducted.

2. The axis or axes of testing.

3. Identification of the tests by number in chronological order.

4. Loading information coded for reference to a time history, shock spectrum, or other authorized loading requirement shown elsewhere in the report; the percent of full-scale level should also be shown.

5. A brief description of every failure. Corrective action need not be listed, since it should be provided elsewhere in the report.

6. The test engineer's opinion about whether the unit's failure is qualifying (Q) or lingering (F). When there is sufficient doubt, the engineer should consult an expert.

7. The test engineer's opinion about whether the failure is consistent (C) or independent (I). Again, consultation with an expert may be necessary. This information is not complete until the scheduled testing is finished and the types of failures are reviewed. Further testing may be recommended if independent failures are recognized.

Hardness Assurance or Assessment

If testing will be conducted by the unit's manufacturer, achieving hardness assurance may be possible. In this case, all consistent failures should be identified and eliminated by redesign, and the unit retested for verification of hardness. The report should include the results of the original design's test if the unit is already operational at any critical facility. Authorization for the mass production and purchasing of hardened units must not be automatically assumed by a manufacturer, since further contract negotiations will be necessary before hardening all production units.

If independent failures are identified, hardness assurance may be difficult or impossible to achieve with available time and funds. In this case, the testing facility should request authority for more extensive testing than originally planned. The goal will then be to

collect enough test data to provide a reasonably accurate hardness assessment. If test analysis capability for hardness assessment does not exist and independent failures occur, the hardness assessment and calculation of the probability of failure may be accomplished later if a complete and accurate report is prepared when the tests are performed.

6 SUMMARY AND CONCLUSIONS

This report has presented procedures for establishing test criteria for seismic qualification of essential equipment in critical facilities and provided guidance for interpreting test results. The following sections summarize conclusions drawn in developing these procedures and guidance.

Procedures for Establishing Seismic Test Criteria

The major tasks in the seismic qualification testing of essential equipment were identified as (1) test criteria formulation, (2) test facility selection, (3) test unit formulation, (4) establishment of test qualification requirements, and (5) interpretation of test results. Development of test criteria was identified as being composed of four subtasks: (1) test axis selection, (2) statement of operating configuration, (3) definition of expected failure modes, and (4) description of the shock environment which can be transformed into a time history waveform to drive a shake table. The first three subtasks must be established on a case-by-case basis and have not been addressed in detail in this report.

A test waveform can be generated from a frequency domain description of the environment and a time-dependent intensity function. The frequency domain presentation can be in the form of a floor response spectrum or a spectral density. The uncertainties in estimating ground motion and building structural parameters can be accounted for by increasing the statistical confidence (or percentile level) of the frequency presentation. The state of the art of generating floor response spectra for inelastic structures has been provided, together with an example problem. The use of spectral density, which requires time history solutions of floor motion, has been limited to academic studies and was therefore simply outlined.

The intensity function may be roughly estimated if floor response spectra are used. This function can be calculated directly if time history floor motions are available.

The conversion of the frequency presentation and the intensity function to generate a test waveform was outlined. Use of the SIMQKE computer program appears suitable for this task. If a time history floor acceleration trace is available, it may be used directly to drive a shake table if the resulting motions are within the physical limits of the test facility. Statistical confidence can be increased by increasing the amplitude of this trace, but the degree of confidence achieved is difficult to estimate without obtaining a spectral density.

Interpretation of Failure Data

Units tested in the SG/TSE program are similar to those found in hospitals and other related critical facilities. The shock environment was not the same as expected from earthquake motion; the SG/TSE environment was more severe above 4.0 Hz and less severe below this frequency. Nevertheless, the experience was considered valuable for guidance in future test projects.

The organization and execution of the SG/TSE program led to development of a glossary of terms and an amplification of test report requirements. The judicious selection of test units appeared to be an important economical consideration. The test reports showed that failures could be clearly labeled in most cases as qualifying or lingering, and as consistent or independent. These labels reflect the significance of a failure in functional performance and repeatability, respectively.

Failure data from proof or fragility testing cannot be associated uniquely with a precise test level. Instead, a failure must be regarded as possible at any other test level at or below the actual test level at which it occurred. Hence, the test level is an upper bound of failure, when failure occurs from this type of testing. In contrast, a failure from strengths or fatigue testing is associated with a unique load level at which the failure occurs. Confusion between these two distinct types of test results should be avoided, since the estimation of the probability of failure is different in each case.

APPENDIX:

SG/TSE TEST SUMMARY

General Equipment and Motor Control Center Tests

Two different procedures for hardness assurance testing were identified in the SAFEGUARD program.[33] In this program, many off-the-shelf items of support equipment were tested which are similar to those used in essential systems of critical facilities. Even though the test envelopes for SAFEGUARD were not what would be required for critical facilities, the experience and qualitative results should be directly applicable.

The method used for most units involved proof testing at 25, 50, 75, and 100 percent of the expected shock environment. The second method was used exclusively on five motor control centers, each of which was submitted to more than four test levels at and below the 100 percent level. The types of failures recorded in each group were significantly different.

General Equipment Tests

Fifty-eight independent units were proof tested. Table A1 lists these units, most of which were similar to equipment considered essential for hospitals (see Table 1).

Column 1 of Table A1 lists the units of equipment in numerical order. Each unit was assigned a distinct full test level, and every item of equipment within a unit received the same shock environment in its appropriate mounted configuration.

Column 2 provides a brief description of each test unit. Indented under the test unit description is a listing of the primary items of equipment contained in the unit. The listing of equipment is necessarily abbreviated, with code letters designated to the equipment for brevity.

[33] Subsystems Hardness Assurance Analysis, HNDSP-73-161-ED-R (U.S. Army Corps of Engineers, Huntsville Division, December 1974).

Table A1

SG/TSE Test Units

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	
Test Unit	Description	Test Level	No. Tests	Mode	Degraded S	Degraded F	Failed S	Failed F	P,Q,F	Remarks	
1	Piping Segments:										
	a. Chilled water seg.	25%	2	B					P		
	b. Digital rack cooling sys seg	50	3	B					P		
	c. Compressed air sys seg	75	8	B					P		
		75/100	3	B	1	1			Q	1) Tank-pipe joint leak 2) Broke I06PI indicator	DS DF
		100	4	B			4		F	1) Tank-pipe joint shear 2) Tank-pipe joint separation 3) Tank mounting failure	FS 2 x FS FS
2	Chilled Water Circ. Sys. (I57FS, P11VJ, P76VC I04PI, P13VN, P56EJ, P39PC, P57EJ, P43SS, P07VB)	25	6	B					P		
		50	5	B					P		
		75	4	B	1	2			Q	1) Water leakage 2) I04PI damaged 3) Pump cavitated	DS DF DF
		100	12	B	3	1			Q	1) Pump mounting bolt sheared 2) Bolts cracked 3) U-bolts and braces bent 4) I04PI damaged badly	DS DS DS DF
3	Cooling Water Circ. Sys. (P57VJ, P10VW, P14VN, I04PI, P30PC, P09VB, P31SS, P13VN, I37AP, P70VG, P09VI, P66VG)	25	4	B					P		
		50	9	B	1	2	1		F	1) Water line broke 2) Air vent leaked water 3) Pressure transducer sheared off	FS DF DF
		75	5	B		1	3		F	1) Pipe loosened in pump seal leak system 2) Air vent pipe broke 3) Motor-pump coupling broke 4) Motor mounts broke	DF FS FS FS
		75/100	9	B		1	2		F	1) Air vent broke 2) Water line sheared 3) Check valve P10VW would not check flow	FS FS DF

Table Al (Cont'd)

Column 1	2	3	4	5	6	7	8	9	10	11
Test Unit	Description	Test Level	No. Tests	Mode	Degraded S	Degraded F	Failed S	Failed F	P,Q,F	Remarks
4	Water Chiller - P04CW	50%	4	U		1			Q	1) Control panel overload relay opened DF
		75	5	U	1				P	1) Welds broken DS
		100	7	U		7			Q	1) Control panel overload relay opened 7 x DF
5	Piping Segments:									
	a. Test pkg. 1, group 1	-6 dB	1	U					P	
		-3 dB	2	U					P	
		-2 dB	1	U					P	
		100	7	U	3	9			Q	1) Pipe leakage 3 x DS
										2) Switch chatter on I51FS 4 x DF
										3) Flow setting on I51FS changed 3 x DF
										4) I07PI read high DF
										5) I07PI needle bound DF
	b. Same retest of I51FS	75	2	U					P	
		100	5	U		2			Q	1) Switch actuation on NO and NC contact 2 x DF
	c. Test pkg 1, Group 2	-6 db	4	U					P	
		100	8	U					P	
	d. Test pkg. 2, MSCB	25	4	U				3	F	1) Severe leakage of P40PC 3 x FF
		50	8	U				7	F	1) Severe leakage of P40PC 7 x FF
		75	6	U				6	F	1) Severe leakage of P40PC 6 x FF
		100	13	U	1	3		12	F	1) Severe leakage of P40PC 12 x FF
										2) Pr. transd. cause saturation of charge amps DF
										3) System pressure fluctuation 2 x DF
										4) Bolts sheared off DS
	e. Test pkg. 3, PARPP	50	1	U					P	
		75	2	U					P	
		100	6	U	1	3			Q	1) I04PI pressure indicated drop 2 x DF
										2) Lower link screw backed out DS
										3) Wire cut on balance amplifier DF

Table A1 (Cont'd)

Column 1	2	3	4	5	6	7	8	9	10	11	
					Degraded		Failed				
Test Unit	Description	Test Level	No. Tests	Mode	S	F	S	F	P,Q,F	Remarks	
6	Peripheral Pumps										
	a. Turbine pumps	25%	1	B					P	(P03PT only)	
	P01PT, P03PT	100	7	B					P		
	b. Pos. disp. pumps	100	4	B					P		
	P01PR, P03PR										
7	Waste Disposal Pumps	50	1	U					P		
	P02PS, P03PS	75	2	U				1	F	1) P02PS seized, attributed to poor lubrication	FF
		(see remark)								(Pumps not operated in subsequent tests)	
		50	2	U					Q		
		75	3	U					Q		
		100	6	U					Q		
8	Pressure Control Valve	50	2	U					P		
	P83VE	75	3	U					P		
		100	7	U					P		
9	Thermal Water Valve	50	2	B					P		
	P01CR	75	2	B					P		
		100	5	B					P		
10	Air Compressor Control	50	5	U		1			Q	1) HI after cooler temp. fault tripped	DF
	Panel - Drive motor										
	P01CR	75	6	U		3			Q	1) HI after cooler temp. fault tripped	2 x DF
										2) Disable vibration sw. fault	DF
		100	8	U		1			Q	1) Disable vibration sw. fault	DF
11	Instrument Air Dryer	50	2	U					P		
	P01DA	75	3	U					P		
		100	9	U					P		

Table A1 (Cont'd)

Column 1	2	3	4	5	6	7	8	9	10	11
Test Unit	Description	Test Level	No. Tests	Mode	Degraded S	Degraded F	Failed S	Failed F	P,Q,F	Remarks
12	Compressor - Inst. Air Dryer	50%	1	U					P	
	P03DA	75	1	U					P	
		100	3	U					P	1) Pressure sw. tripped shutting off compressor--turns on automatically when pr. drops to 71 psi
		140	2	U					P	1) (Same)
13	Compression Control Oil	50	1	B					P	
	Shutdown Switch - P01CR	75	1	B					P	
		100	5	B		2			Q	1) Lowered oil level just above sw. actuation pt. 2 x DF 2) (No count) switch actuation
14	Heat Sensing Device Assy	50	2	B					P	
	(Fire Protection Sys.)	75	2	B					P	
		100	4	B					P	
15	Temperature Switch	50	2	B					P	
	I58TS	75	3	B		1			P	1) Contact chatter DF
		100	5	B		1			P	1) Contact chatter DF
16	Air Handling Unit	10	3	B					P	
	H06AU	50	2	B					P	
		75	2	B	3		1	1	F	1) Motor belts separated FF 2) Filter retaining plate separated DS 3) Filter section center brace loosened DS 4) Mounting bracket distorted DS 5) Lower coil section leak FS
		100	12	U	5			6	F	1) Motor belt separated FF 2) Filters separated 5 x FF 3) Filter retaining plate separated 5 x DS

Table A1 (Cont'd)

Column 1	2	3	4	5	6	7	8	9	10	11
Test Unit	Description	Test Level	No. Tests	Mode	Degraded S	Degraded F	Failed S	Failed F	P,Q,F	Remarks
17	Air Conditioner	(#1)	1	B					P	
		(#2)	1	B		1			Q	1) Wellnut fastener pulled out, cracked DF
18	Monitor and Control-Duct Mounted Equipment									
	a. Test pkg. 1	75%	3	U	2	1			Q	1) Movement of extractor and diffuser 2 x DS
										2) No output from 114PT pr. transd. DF
		100	6	U	6	1	1		F	1) Movement of extractor and diffuser 6 x DS
										2) 107TT temp. transd. damaged DF
										3) Regulator sheared off FS
	b. Test pkgs. 3 and 4	75	4	U		4			Q	1) Vanes closed on top register 4 x DF
		100	8	U		9			Q	1) Vanes closed on top register 8 x DF
										2) Fire damper door closed DF
	c. Test pkg. 2	50	3	U					P	
		100	6	U		1			P	1) Sensing element cracked from joint DF
19	Dry Transformers (8 items total)	50	2	U					P	
		75	3	U					P	
		100	6	U	4		1		Q	1) Mounting legs broken, item 1 FS
										2) Screws sheared in lower and main housing, item 1 DS
										3) Attach bracket bent, item 3 2 x DS
										4) Bolt sheared, item 8 DS
		140	2	U	2				Q	1) Interference between interface and housing, items 5,6,8 2 x DS

Table A1 (Cont'd)

Column 1: Test Unit	Column 2: Description	Column 3: Test Level	Column 4: No. Tests	Column 5: Mode	Column 6: Degraded S	Column 7: Degraded F	Column 8: Failed S	Column 9: Failed F	Column 10: P,Q,F	Column 11: Remarks
20	Flourescent Light Fixtures	50%	9	B		4			Q	1) Lamps broke, disengaged, fell out 4 x DF
		75	17	B		9			Q	1) Lamps broke, disengaged, fell out 9 x DF
		100	32	B		20			Q	1) Lamps broke, disengaged, fell out 20 x DF (most fixtures were hardened before these tests run)
21	Generator Control Panel LO1GD	25	3	U					P	
		A	4	U					P	
		75	3	U					P	
		B	7	U		1			P	1) Agastat relay indicated open DF
22	Metal Clad Switchgear:									
	a. 5HK75, Item E & Aux. Unit	-6 dB	3	U		2			Q	1) Fault indicator flags down* 2 x DF
		A	6	U		7			Q	1) * 7 x DF
										2) Electrical fault** 3 x DF
		B	7	U		14			Q	1) * 7 x DF
										2) ** 7 x DF
		C	6	U		12		1	Q	1) * 6 x DF
										2) ** 6 x DF
										3) Plastic contact housing broken DS
	b. 5HK350, Item D Aux. unit, Item B	-6 dB	1	U					P	
		A	6	U		8			Q	1) * 6 x DF
										2) ** 2 x DF
		B	6	U	1	6			Q	1) * 5 x DF
										2) ** DF
										3) Front door panel jammed DS
		C	6	U	3	7			Q	1) * 5 x DF
										2) ** 2 x DF
										3) Front door panel jammed 2 x DS
										4) Tilting bracket assy broken DS
	c. 15HK500	-6db	2	U					P	
		A	6			6			Q	1) * 4 x DF
										2) ** DF
		B	6	U		9			Q	1) * 6 x DF
										2) ** 3 x DF
		C	6	U		10			Q	1) * 6 x DF
										2) ** 4 x DF

Table A1 (Cont'd)

Column 1	2	3	4	5	6	7	8	9	10	11	
Test Unit	Description	Test Level	No. Tests	Mode	Degraded S	Degraded F	Failed S	Failed F	P,Q,F	Remarks	
23	Generator Neutral Breaker R01GD	25%	4	U		1			P	1) Relay chatter	DF
		A	7	U		5			P	1) Relay chatter	5 x DF
		75	4	U		5			Q	1) Relay chatter	4 x DF
										2) Circuit breaker trip	DF
		B	2	U		2			P	1) Relay chatter	2 x DF
		100	4	U		5			Q	1) Relay chatter	4 x DF
										2) Circuit breaker trip	DF
24	Generator Static Excitor - Regulator R01GD	25	4	U		1			P	1) Relay chatter	DF
		A	7	U		1			P	1) Relay chatter	DF
		75	3	U		1			P	1) Relay chatter	DF
		B	10	U		1			P	1) Relay chatter	DF
25	Circuit Breakers R27SS	25	2	B					P		
		50	4	B					P		
		75	6	B		1		1	Q	1) Breaker unit 3 dropped out	FF
										2) Breaker unit 1 contacts damaged	DF
		100	11	B		1		9	F	1) Breaker unit 3 contacts damaged	DF
										2) Breaker unit 3 dropped out	4 x FF
										3) Breaker unit 3B dropped out	5 x FF
										4) All breakers dropped load	FF
26	Circuit Breakers R29SS	20	1	B					P		
		50	11	B		1			Q	1) Contact 1 unit 5 broke open	DF
		75	2	B		1			Q	1) Contact 1 unit 5 broke open, bent	DF
		100	2	B		1	1	3	F	1) Contacts destroyed, units 2, 3,5, cubical A	FF
										2) Cabinet control circuitry destroyed	FF
										3) Close and trip lights did not function	DF
										4) Trip shaft dislodged	FS
										5) Mech. failure of breakers in unit 5, cabinet D	FF

Table A1 (Cont'd)

Column 1	2	3	4	5	6	7	8	9	10	11	
Test Unit	Description	Test Level	No. Tests	Mode	Degraded S	Degraded F	Failed S	Failed F	P,Q,F	Remarks	
27	Motor-Generator Set E03GM	25%	3	B					P		
		50	5	B		5			Q	1) Relay flags tripped	5 x DF
		75	6	B		6			Q	1) Relay flags tripped	6 x DF
		100	13	B	1	13		1	F	1) Relay flags tripped	13 x DF
										2) Cabinet door bolts sheared	VS
										3) Main breaker dropped load	FF
28	Gas Turbine Electrical Generator	25	2	B					P		
		50	2	B					P		
		75	3	B					P		
		100	2	B					P		
29	Electrical Motor Control Center - R05SS	10	2	B					P		
		25	3	B					P		
		50	3	B					P		
		75	6	B					P		
		100	5	B					P		
30	Motor Generator Set E12GM										
	a. Starter and Exciter	25	6	B					P		
		50	11	B	1	2			Q	1) Relay flags tripped	2 x DF
										2) Door hinge broke	DS
		75	7	B	2	6			Q	1) Relay flags tripped	6 x DF
										2) Cabinet door opened	2 x DS
		100	11	B	2	11		1	Q	1) Relay flags tripped	11 x DF
										2) Cabinet door opened	2 x DS
										3) Trip and control room lights went off	FF
	b. Surge Pak	25	2	B					P		
		50	3	B					P		
		75	5	B					P		
		100	15	B					P		

Table A1 (Cont'd)

Column 1 Test Unit	2 Description	3 Test Levels	4 No. Tests	5 Mode	6 Degraded S	7 Degraded F	8 Failed S	9 Failed F	10 P,Q,F	11 Remarks	
31	Electrical Unit Substation E04SS										
	a. First series	25%	2	B					P		
		50	4	B		1			P	1) Input sw. contacts chattered	DF
		75	3	B					P		
		100	6	B		1			P	1) Blew fuse	DF
	b. Second series	25	3	B					P		
		50	2	B					P	Some relay chatter and	
		75	4	B					P	disconnecting contact damage	
		100	10	B		1			P		DF
32	Components of Unit Substation	25	2	B					P		
	(voltage regulator and	50	7	B					P		
	circuit breaker section)	75	4	B		2			Q	1) Breaker tripped	2 x DF
		100	10	B		7			Q	1) Breaker tripped	DF
										2) Relay chatter	3 x DF
										3) Relay dropped out	3 x DF
33	Motor Control Center E12SS	25	3	B		1			P	1) Chatter	DF
		50	5	B					P		
		75	9	B					P		
		100	11	B		3			P	1) Chatter	3 x DF
34	Unit Substation Transformer E16SS	25	13	B		4			Q	1) Sudden pressure relay dropped out	4 x DF
		50	6	B		6			Q	1) Sudden pressure relay dropped out	6 x DF
		75	8	B		8			Q	1) Sudden pressure relay dropped out	8 x DF
		100	17	B		17		1	F	1) Sudden pressure relay dropped out	17 x DF
										2) Mounting brackets failed	FS
35	Monitoring and Control Comps.										
	a. Group I Pkg.	-6 dB	5	B			2		F	1) Pipe broke from P62CV	2 x FS
		100	4	B			1		F	1) Pipe broke from P62CV	FS
	b. Groups II and III	-6 dB	2	U					P		
		100	5	U		1			Q	1) Control link damage on I03TL	DF
		140	3	U		1			Q	1) Control link damage on I02TL	DF

Table A1 (Cont'd)

Column 1	2	3	4	5	6	7	8	9	10	11	
Test Unit	Description	Test Levels	No. Tests	Mode	Degraded S	Degraded F	Failed S	Failed F	P,Q,F	Remarks	
	c. Group I Pkg II	50%	3	B					P		
		75	4	B					P		
		100	5	B		2			Q	1) Change in temp. setting on 158TS	2 x DF
36	Monitoring and Control Comps.										
	a. Outside Air Makeup I63 PL	50	6	U					P		
		75	5	U	1				P	1) Swivel adaptor cracked	DS
		100	10	U	2	2			Q	1) Lower front panel fell off (fasteners)	DS
										2) Cracks in lower framework	DS
										3) Change in output differential pressure	2 x DF
	b. Local Instrument Panels I50PL, I53PL	50	3	B					P		
		75	2	B					P		
		100	4	B	2				P	1) Upper door hinge distorted	DS
										2) Upper door hinge bolt stripped	DS
	c. Pressure Switches I54AP, 003JD	50	2	B					P		
		75	3	B		1			Q	1) Index indicator dislodged	DF
		100	8	B		7			Q	1) Chatter on R-2	3 x DF
										2) Index indicator dislodged	5 x DF
	d. Pneumatic Control Valve P83CV	50	2	B					P		
		75	2	B					P		
		100	4	B					P		
	e. Pneumatic Actuator I18DA	50	2	U					P		
		75	2	U					P		
		100	4	U					P		
	f. Butterfly Valve P12VQ	50	3	U					P		
		75	5	U					P		
		100	7	U					P		
	g. Indicating Control Assy I03CL	50	2	B					P		
		75	3	B					P		
		100	7	B		1			Q	1) Indicator cam follower fell off cam	DF

Table A1 (Cont'd)

Column										
1	2	3	4	5	6	7	8	9	10	11
Test Unit	Description	Test Level	No. Tests	Mode	Degraded S	Degraded F	Failed S	Failed F	P,Q,F	Remarks
36	(Cont'd)									
	h. Butterfly Valve	50%	2	B					P	
	P22VQ	75	2	B					P	
		100	6	B					P	
	i. Plug Valve	50	4	B					P	
	P05VJ	75	4	B					P	
		100	8	B					P	
	j. Diff. Pr. Transm.									
	PC13150252-7	50	2	B					P	
	Temp. Transm	75	2	B					P	
	I01CV	100	4	B					P	
	k. Plug Valve	50	3	U					P	
	P65VJ	75	3	U					P	
		100	11	U					P	

Column 3 shows the test levels used in order of increasing percentages of the full proof test level assigned. A composite envelope of these spectra is given in Figure 1 in the main text. Column 4 gives the number of tests held at each test level. Column 5 shows the mode of testing--either a uniaxial (U) or biaxial (B) environment was provided.

Columns 6 and 7 list the number of structural (S) and functional (F) failures which degraded the equipment in some respect, but did not render it or any interfacing equipment inoperable for a significant period of time. These failures have been defined (Chapter 3) as "qualifying." In a similar manner, columns 8 and 9 list failures, defined as "lingering," which obviously required equipment downtime for repair. Column 10 summarizes the information of the previous four columns by showing that the equipments passes (P), passed qualified (Q), or failed (F) the test environment. The remarks of column 11 provide brief descriptions of the failures of all types encountered.

The following summary was derived from the information in the table. Of the units tested, 26 passed all levels (45 percent), while two failed all levels (3 percent).

A total of 968 tests were held on all units, often in orthogonal directions. Tests were held primarily at the four levels mentioned above. A few tests were held below the 25 percent level, and others were held as high as the 140 percent level. A total of 430 failures were recorded. Of the failures, 84 percent could be repaired immediately, or had a degrading effect which did not seriously impair the unit's function (qualifying failures). The remaining 16 percent of the failures produced lingering effects and required a significant amount of time to correct.

Table A2 lists the percentage of failures at each of the four primary test levels, together with the percentage of qualifying failures (Q) and the percentage of lingering failures (F). At the 100 percent level, for example, there were 411 tests yielding 225 failures (54.7 percent). Of the failures, 33.3 percent were qualifying, while the remaining 21.4 percent produced lingering effects.

Table A2

Failure Summary from General Equipment Tests

Full Test Level	No. of Tests	Combined Failures	Qualifying Failures (Q)	Lingering Failures (F)
25%	70	5.7%	5.7%	0.0%
50%	163	20.2%	14.1%	6.1%
75%	197	37.1%	31.5%	5.6%
100%	411	54.7%	33.3%	21.4%

Motor Control Center Tests

Five independent motor control centers were tested, with failures recorded for all units.

One hundred and seventy-two tests were held at numerous test levels in three orthogonal axes; an average of 34 tests (11 in each axis) was held for each unit. A total of 92 failures (53 percent) was recorded, 22 (13 percent) of which were qualifying, and 70 (40 percent) of which produced lingering effects. The further breakdown of percentages for qualifying and lingering failures does not appear to be meaningful, since correlation with test levels is necessary. In this case, the numerous and inconsistent variety of test levels rendered such a tabulation impractical.

Types of Failures

Failures have already been classified as qualifying or lingering according to ease of repair or time delay. It is desirable to report all failures for future reference. However, in current procedures for recording failures, the required time for repair is usually not indicated. Therefore, it is often difficult to review test reports for the purpose of identifying trivial or significant failures. This experience led to the proposed specification that the test engineer record his/her opinion about the amount of repair time required. The opinion

can be reviewed and corrected by more qualified personnel, if necessary. Even knowledge that the time delay was unknown would be helpful.

Failures observed in the SAFEGUARD data could be classified further according to consistency or independence. Often, more than one consistent failure was observed to occur at a single test level. It is roughly estimated that more than 90 percent of the failures which occurred during the general equipment tests were of this type. The estimate is rough because the recorded results were not oriented so that this type of failure could be clearly identified. When such a failure occurs, there is no doubt that it must be eliminated by hardening or isolating the unit to withstand the environment.

In contrast, the failures recorded from the motor control center tests were very inconsistent; i.e., the same failure might or might not occur more than once at the same level or at different levels. Usually, repairing the failure after one test would have no significant influence on whether or not the same failure would occur for any other test. In general, the higher the test level, the greater the probability of having one or more failures of this type. Statistically, such failures are independent. Estimating the probability of failure is more difficult in this case, requiring the use of conventional methods of probability and statistics. When independent failures occur, it is especially important to conduct a sufficient number of tests at preferred test levels to more accurately predict the probability of failure.

CERL Special Report M-209 provides a statistical method for estimating the probability of failure for independent failures and for calculating the accuracy of the estimation. The results of this analysis provide criteria for planning the number of tests and test levels when independent failures occur.

Typical Failure Modes

Eventually, it will be necessary to generate specifications for designing, mounting, and procuring critical equipment; however, it is not feasible to consider providing specifications for all such equipment

in the near future. A more reasonable approach would be to determine what failures have occurred most often during testing or from direct exposure to the hazardous environment. Priorities may then be established for attacking the various modes of equipment failure in order of importance.

The most complete listing of equipment failure modes encountered until now appears to be from SAFEGUARD test data. On the component level, failure modes observed in the SAFEGUARD data are:

1. Piping failures:

   Joint leakage
   Joint shear
   Joint separation
   Pipe burst
   Braces bent
   Brace bolt sheared
   Valve failure (check)
   Valve chatter

2. Indicator failures

   Pressure
   Temperature
   Liquid level
   Flow rate

3. Sensing device failures:

   Transducer shear-off
   Wires cut
   Inadvertent switch actuation

4. Machinery failures:

   Pump cavitation
   Pump leakage
   Motor-pump coupling failures
   Motor-generator coupling failures
   Pump flow setting change
   Pump seizure
   Motor belt drive separation

5. Mounting failures:

   Tank mounting failure
   Pump mounting bolt shear
   Motor mounts broken
   Legs, brackets broken
   Displacement interference

6. Electrical failures:

   Switch contact chatter
   Relay chatter
   Relay trip
   Circuit breaker trip
   Lights broken.

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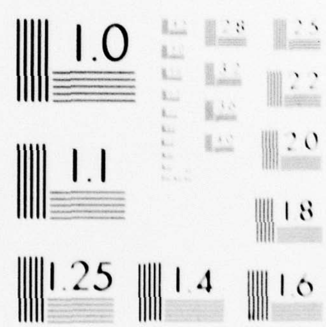

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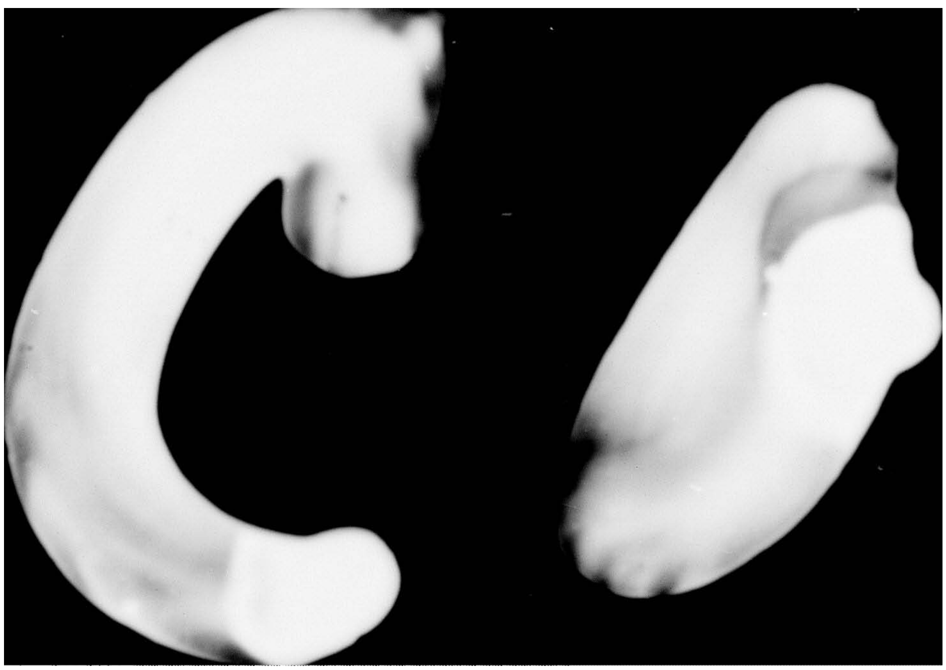

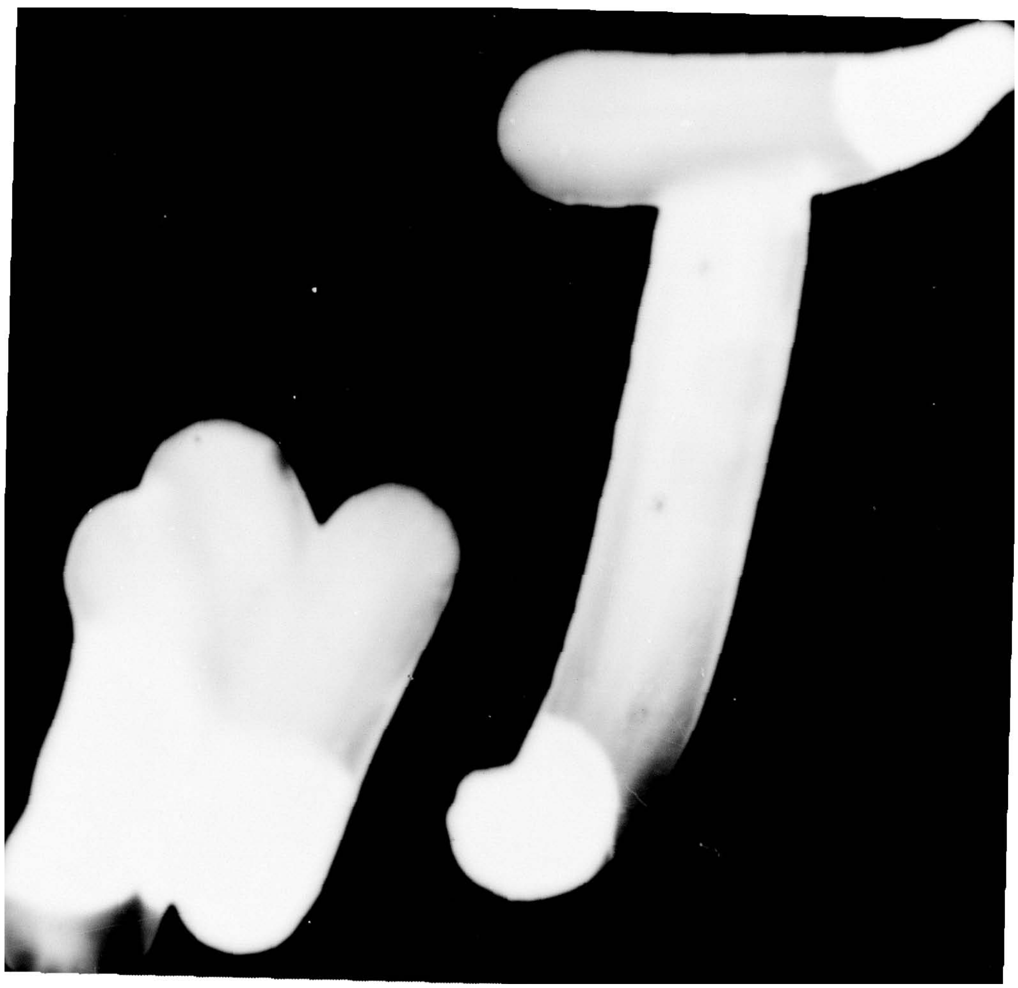

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1. Page 31 - Add the following sentence at the end of the definition of Floor Response Spectrum: That is, an equipment response spectrum is referred to synonymously with a floor response spectrum, while a building response spectrum is referred to synonymously with a ground response spectrum.

2. Page 51 - Delete reason 4, and change reason 5 to reason 4.

3. Page 51 - 59 - Note that the expression "equipment response spectrum" is used synonymously with "floor response spectrum."

4. Page 53 - Delete existing Step 6 and replace with the following:

Step 6. Compute the ordinates of the equipment response spectrum at each of the building's natural frequencies from the relationship

$$z_j = K_j a_j \qquad \text{[Eq 24]}$$

where z_j = equipment response spectrum ordinate for any floor level of the jth mode

K_j = amplification factor for jth mode from Step 5

a_j = response spectrum acceleration level at the jth mode frequency.

Note that z_j is not given as a function of floor level. This is because calculations have shown that z_j has approximately the same value for any floor of interest.

5. Page 58 and 59 - Delete existing Step 6 and replace with the following:

Step 6. K_j and a_j were determined in Step 4 and Step 5, respectively. The floor response spectrum ordinates are determined using Equation 24:

$$z_1 = (7.21)(0.82) = 5.91 \text{ g}$$
$$z_2 = (3.90)(0.82) = 3.20 \text{ g}$$
$$z_3 = (2.48)(0.76) - 1.88 \text{ g}$$

6. Please replace Figure 14 with the attached.

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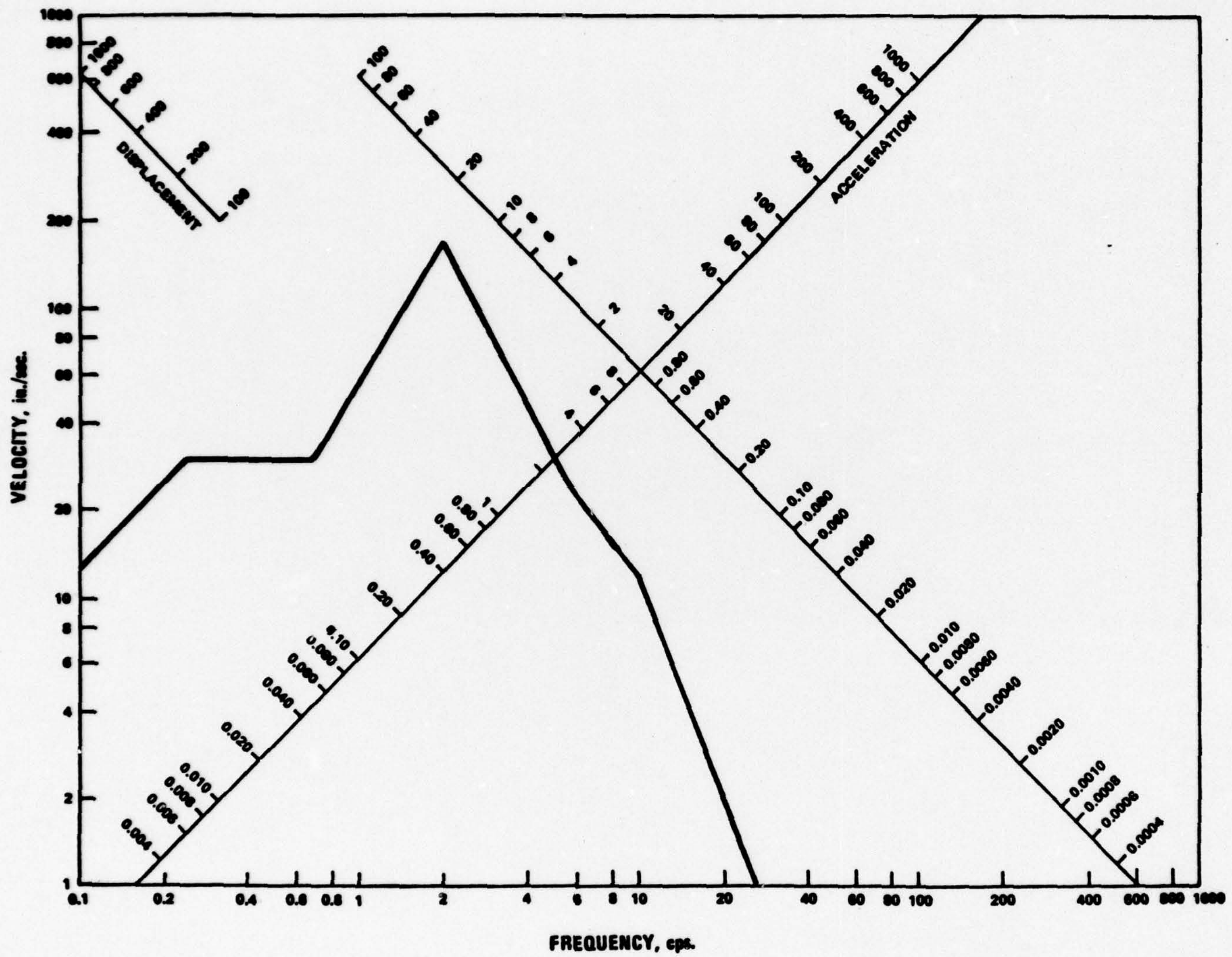

Figure 14. Equipment response spectrum. SI conversion factor: 1 in. = 25.4 mm.